NEUTRON STARS
AND PULSARS:
CHALLENGES AND
OPPORTUNITIES
AFTER 80 YEARS

Edited by: JOERI VAN LEEUWEN
**COVER ILLUSTRATION:** 1932 - 2012:

DISCOVERY OF THE NEUTRON - A NEUTRON STAR IN A supernova

This diptych combines the 1932 detection of the neutron with the state of modern neutron-star and pulsar research, in 2012.

In the left-hand side photograph, neutrons have collided with the atoms in a layer of paraffin wax, ejecting a proton. The proton path is visible in the ionization chamber.

The right-hand panel shows an optical (HST) and X-ray (Chandra) false-color image of supernova remnant 1E 0102-7219. Overlaid for illustration is radio (WSRT) data of the Crab pulsar.

Left image courtesy of I. Joliot-Curie & F. Joliot/NMSI. Right image of SNR E0102 courtesy of NASA/CXC/STScI/MIT/SOA/D.Dewey/J.DePasquale; overlay of Crab pulsar radio data courtesy of J. van Leeuwen/ASTRON.
NEUTRON STARS AND PULSARS: CHALLENGES AND OPPORTUNITIES AFTER 80 YEARS

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Preface

The neutron hit the paraffin wax. It had been cast out when the alpha particle and beryllium nucleus had merged. In the wax, the neutron smashed out a proton. It traveled through the round bubble chamber, its mark captured on photographic plate. It’s 1932, and the neutron is discovered.

A massive star exploded, and left a round supernova remnant. The neutron star was smashed out from the center of the crash. It spins and sends a beam of radio emission racing through the galaxy, to the telescope, arriving in 2012.

These two images, so visually similar as the front cover makes clear, mark the begin and current state of 80 years of neutron star research. That status, those newest results in neutron-star and pulsar studies, were presented at the IAUS291, Beijing, August 2012.

Several of the outstanding presentations in this volume are clearly linked to previous highlights in the lifetime of this octogenarian field. Chamel uses the sudden spin changes seen in some radio pulsars to constrain how the neutrons inside the star behave – 80 years after the initial idea by Landau that such stars might exist. And while Baade and Zwicky proposed in 1934 that neutron stars form in supernovae, Sumiyoshi now presents our, partial, understanding of the mechanism driving these explosions. The new LOFAR discoveries presented by Kondratiev, and by Coenen, were made using a telescope operating at the same frequencies, and build as a similar array of dipoles, as the original Cambridge array with which Hewish and Bell found the first radio pulsar in 1967. Backer, much missed, found the first, isolated millisecond pulsar in 1982 – a discovery that echoed in Roberts’ review on the now numerous detections of black-widow millisecond pulsars.

Other results, however, are exceedingly novel. Saz Parkinson presented tens of gamma-ray pulsars that were blindly detected with Fermi-LAT, uncovering a new population that is nearby and energetic, and often radio-quiet. An entire session, headed off by Hobbs, showcased the potential for gravity-wave pulsar astronomy. In several talks the intriguing new-found relations between spin-down and profile evolution were discussed. Burke-Spolaor, and Karako, explained how some radio pulsars only emit sporadically.

On August 24, 2012, 17:12 Beijing time, this IAU Symposium 291 came to a close. Yet, the talks and posters remain, in several complementary forms: as both slides and video online†, and as proceedings in the volume before you.

*Joeri van Leeuwen*

*21 November, 2012*

† [http://www.pulsarastronomy.net/IAUS291](http://www.pulsarastronomy.net/IAUS291)
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Welcome

The title of IAU Symposium 291 “Neutron Stars and Pulsars: Challenges and Opportunities after 80 Years” encapsulates the spirit of this Symposium: the 80 years since the idea of neutron stars was born and, in particular, the 45 years since pulsars were discovered have provided us with a rich harvest of scientific discovery, but many exciting avenues for future research remain. The Symposium, held in the huge Chinese National Convention Center adjacent to Beijing’s Olympic Park as part of the 28th General Assembly of the International Astronomical Union, was very successful with more than 160 talks and posters presented over the five days and 14 sessions of the meeting. We are pleased that most of these presentations are represented in these Proceedings.

The sessions covered current searches for pulsars, both radio and gamma-ray, neutron-star formation and properties, binary pulsars, pulsar timing and tests of gravitational theories, magnetars, radio transients, radio, X-ray and gamma-ray pulse properties and emission mechanisms, and future facilities. This range of topics illustrates the diverse nature and wide application of pulsar research. Exciting new results were presented in all sessions and it is impossible to list them all. However, I would like to mention the three plenary talks, presented by Scott Ransom, Nanda Ray and Michael Kramer, which were outstanding and given to a standing-room-only audience despite the early hour. As the corresponding articles in this Proceedings show, they managed to successfully communicate the excitement of current pulsar research. I had many comments afterward, mostly from “non-pulsar” people, about how fascinating these talks were. I would also like to give special mention to Jocelyn Bell-Burnell’s highly original closing remarks. We are grateful to her for allowing us to include them in this Proceedings.

Finally, I would like to give my thanks to the IAU and the GA Local Organising Committee for a well-run and successful meeting, to the Scientific Organising Committee for Symposium 291 for their assistance with putting together an excellent scientific programme, to all the presenters for realising the potential of the programme and to the Editor of the Proceedings, Joeri van Leeuwen, for all the hard work required to bring this volume to fruition. I hope and expect that it will be a valuable reference work for both current and future students and researchers in astronomy and astrophysics.

R. N. (Dick) Manchester
16 November, 2012
Plenary Presentations
Pulsars are cool. Seriously.

Scott M. Ransom

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Abstract. Ever since the first pulsar was discovered by Bell and Hewish over 40 years ago, we've known that not only are pulsars fascinating and truly exotic objects, but that we can use them as powerful tools for basic physics and astrophysics as well. Taylor and Hulse hammered these views home with their discovery and timing of the spectacular “binary pulsar” in the 1970s and 1980s. In the last two decades a host of surprises and a promise of phenomenal scientific riches in the future has come from the millisecond pulsars. As our instrumentation has become more sensitive and better suited to measuring the pulses from these objects, they've given us new tests of general relativity, fantastic probes of the interstellar medium, constraints on the physics of ultra-dense matter, new windows into binary and stellar evolution, and the promise of a direct detection of gravitational waves. These things really are cool, and there is much more we will do with them in the future.

Keywords. pulsars: general, words: superlatives and colloquialisms

Pulsars really are cool. Not in the temperature sense, given that their surfaces are at about a million kelvin, but in the other. These are city-sized ($10^{12}$ km radii) neutron stars with up to twice the mass of our Sun. Their central densities are several times higher than atomic nuclei, so high that our current nuclear and particle physics cannot accurately predict what goes on deep within these stars. They have surface gravities 100 billion times stronger than the Earth’s, making nearby space-time highly curved. Their magnetic fields range from 100 million times to a quadrillion times stronger than the Earth’s — fields so strong that quantum effects become important (see Nanda Rea’s contribution to these proceedings). They can spin over 700 times per second, which is faster than racing car engines rotate and kitchen blenders spin. They emit electromagnetic radiation via detailed processes we don’t understand after over 40 years of hard work and at luminosities, coming only at the expense of rotation(!), of up to 10,000 times more than the total output of the Sun. There is no denying that these are exotic objects.

Yet even if we ignore their exoticness, they are still cool. The stories of the original pulsar discovery by Jocelyn Bell and Tony Hewish (Hewish et al. 1968) and of the first binary pulsar by Joe Taylor and Russell Hulse (Hulse & Taylor 1975), and the ensuing Nobel glories and gaffes, are the stuff of astronomical legend. For me though, what really makes pulsars so cool is how they can be used as tools for a wide variety of physics and astrophysics problems by the miracle of pulsar timing. The “stars” of these measurements are most certainly the millisecond pulsars (MSPs).

1. Millisecond pulsars

Millisecond pulsars are distinct from the $\sim$2000 “normal” pulsars known in that they have been “recycled” (Alpar et al. 1982 and Radhakrishnan & Srinivasan 1982). A pulsar is born in a supernova and then radiates and spins-down as a normal (i.e. $\sim$1 second spin period) pulsar for 10-100 Myr. If the system was in a binary which survives the supernova though, the secondary star will evolve on Gyr timescales and, when it begins to ascend the
giant branch, transfers mass and angular momentum onto the long-dead pulsar. During this period the system is observable as an X-ray binary. When the stellar and binary evolution finishes, an MSP emerges, spinning hundreds of times per second in a nearly perfectly circular orbit around a white dwarf. Since the neutron star’s magnetic field is somehow buried by the accretion, from $10^{12}$ Gauss down to $10^8$ Gauss, the new MSP spins down much more slowly, providing us with a nearly perfect clock visible for billions of years.

2. Pulsar timing

At 8:40AM CST, on August 23, 2012 (which was when I was at this point in my talk at the IAU in Beijing), the spin period of one of the best timed MSPs, J0437−4715, was exactly 5.7574518556687 ms with an error of ±1 in the last digit. Since the pulsar loses rotational energy due to its emission of a relativistic wind and electromagnetic radiation, that last digit increases odometer-like by one every half hour. That means that the first 6 digits will remain constant for about the next millennium! This stability, and our ability to measure it via pulsar timing, is why pulsars enable truly revolutionary measurements.

Pulsar timing is really quite simple in concept. We unambiguously account for each and every rotation of a pulsar over a time span of years. In practice, we can actually track small fractions of each rotation, thereby making pulsar timing a precise form of phase measurement. With the start of an observation referenced via GPS to worldwide atomic time standards and time during each observation tracked using hydrogen masers at the observatories, we can measure the average times of arrival (aka TOAs) of MSP pulses to better than 1 µs, which corresponds to about $10^{-4}$ in rotational phase $\phi$. Since an error in frequency is simply $\Delta \phi / \Delta T$, if we can make measurements like this over time spans $\Delta T$ of 3 years (i.e. $10^8$ seconds), our measurement error in the spin frequency of a pulsar is $10^{-12}$ Hz, corresponding to about 14 significant figures for MSPs.

We establish timing “solutions” for pulsars via a bootstrapping series of observations scheduled such that we never lose count of the number of rotations our target pulsar makes. A dense set of observations involving several over one or two days, and then several more spaced over the next week allow us to solve binary orbital parameters and determine an increasingly precise spin frequency. As more time is added to the timing solution, the Earth’s orbital motion allows us to determine highly-precise (down to tens of micro-arc-seconds for MSPs) astrometric positions and eventually even proper motions of the pulsars, and the spin-down of the pulsar appears as an increasing quadratic delay in the pulse arrival times. After a year, the timing solution is complete, and it includes a precise position, spin-frequency, and spin-down rate, and many significant figures in the five Keplerian orbital parameters if the pulsar is in a binary (orbital period, projected semi-major axis, eccentricity, time of periastron passage, and the argument of periastron). Often characterized by the root-mean-squared (RMS) deviation of the timing residuals (i.e. TOAs minus model predictions), state-of-the-art timing solutions are below 100 nano-seconds RMS over timescales of 5 or more years.

Published MSP timing solutions are some of the most precise measurements in all of astrophysics and have enabled science which would be effectively impossible using other techniques. A great example is the fact that MSP timing provides pulsar radial velocity measurements at ridiculous precisions of a few mm/s compared to ~1 m/s for optical radial velocity planet surveys. That precision allowed Wolszczan & Frail (1992) to uncover the first extrasolar planets around MSP B1257+12. Those planets are all among the lowest mass exoplanets yet detected, and planet “A” is only twice the mass of the Moon!
3. A millisecond pulsar renaissance

Over the past decade, and especially over the past 5 years, the pulsar field has been focused on MSPs. The simple reason for this is Moore’s Law, since computation and the improved digital instrumentation based on it has dramatically improved our ability to discover and time MSPs. We need to sample our radio data at rates much faster than the already rapid spin rates of MSPs in order to make precise measurements of them. Effective sampling times of \( \sim 50 \mu s \) are now the standard for pulsar searches and times below 1 \( \mu s \) are common for high-precision timing observations.

In addition, since radio pulses propagate through the ionized interstellar medium, they experience dispersion such that the lower radio frequencies \( \nu \) are delayed quadratically (i.e. \( \Delta t \propto \nu^{-2} \)) with respect to the high frequencies. To compensate, we divide our observing band into many independent frequency channels, effectively making spectra for each sample in time, and then delay the channels appropriately so that the pulses sum in phase.\(^\dagger\) For modern pulsar surveys, which are (finally) nearly as sensitive to MSPs as they are to normal pulsars, we require thousands of spectral channels across our observing bands. Combined with fast sampling, data rates of \( \sim 50 \) MB/s are common for each \( \text{pixel} \) in the surveys, and total data volumes can comprise nearly a Petabyte. Computing is extremely important and costly for search processing as well since we must search over thousands of independent “Dispersion Measure” (aka DM) trials since the amount of dispersion is unknown \( \text{a priori} \) for a new pulsar\(\dagger\).

Finally, since pulsars are intrinsically faint but continuum radio sources, we want large observing bandwidths to integrate over in order to maximize the signal-to-noise of our detections. In general, they have steep radio spectra which limits the highest useful observing frequencies to \( \sim 3 \) GHz, while radio interference, interstellar scattering, and the Galactic synchrotron background limit low frequencies to \( \sim 300 \) MHz. Custom state-of-the-art digital instrumentation is required to rapidly sample and channelize bandwidths of hundreds to thousands of MHz and cluster computing is required to process it.

The advances of Moore’s Law over the last decade have resulted in pulsar instrumentation which has been asymptotically approaching perfection given the \( \sim 3 \) GHz of total bandwidth available for pulsar observations. For the first time ever, we are being limited by the sizes of our telescopes rather than the capabilities of the radio receivers or our pulsar instrumentation. The new instrumentation has brought new life to “classic” single-dish radio telescopes used for pulsar observations such as Parkes, Jodrell Bank, and Arecibo, and will finally allow us to use “new” telescopes such as the GBT to their fullest.

Besides dramatically improved sensitivities to new MSPs in the current generation of pulsar surveys, our ability to time MSPs has increased in a Moore’s Law fashion as well. In the 30 years since the discovery of the first MSP by Backer et al. (1982), the typical timing precision for high-precision pulsars has improved by a factor of several hundred, from RMSs of 10s of microseconds to better than \( \sim 100 \) ns. Such timing precision has opened up completely new probes of physics.

\(^\dagger\) For pulsar timing, we can Nyquist-sample the full observing band and perform what is known as coherent de-dispersion to exactly remove the dispersive delays. This technique is incredibly computationally intensive and has only recently become feasible across large observing bandwidths.

\(^\dagger\) Most modern surveys also perform tens to hundreds of so-called “acceleration” trials for each DM trial to improve sensitivities to interesting pulsars in compact binary systems.
4. Case in point: MSP J1614−2230

A beautiful example of how instrumentation can so dramatically change what is possible in pulsar observing is the MSP J1614−2230. It was uncovered in a last-generation survey of EGRET gamma-ray error boxes (Crawford et al. 2006) and appeared to be a fairly “vanilla” MSP with a spin period of 3.15 ms in an 8.7-day circular orbit with a white dwarf. Because of its position in the sky, it was a perfect “test” pulsar to observe for a minute or two to check the GBT’s observing system before starting regularly scheduled long-term observations of MSPs in globular clusters near the Galactic center. After accumulating almost 5 years of not-very-good (i.e. \(~10\mu s\) RMS) timing data in this manner, we noticed systematic delays during a small portion of the orbit when the pulsar passed behind the companion star (i.e. superior conjunction). On three separate days, the pulses arrived later than expected by \(20-40\mu s\). We knew from the orbital parameters and the Keplerian mass function that the companion star was at least \(0.4 M_\odot\), which is quite massive compared to most other MSP companions (which are typically \(0.1-0.2 M_\odot\)).

We conjectured that the systematics were due to the “Shapiro Delay” of the pulses as they passed through the gravitational potential of the white dwarf. Irwin Shapiro first identified this effect in 1964 and then measured it with beautiful radar experiments in the late 1960’s and early 1970’s (e.g. Shapiro et al. 1971). We had just built a brand-new wideband pulsar instrument for the GBT called GUPPI† (Green Bank Ultimate Pulsar Processing Instrument), based on field programmable gate arrays (FPGAs) and high-end graphics processing units (GPUs) made for computer gaming. GUPPI can effectively perfectly process the full 800 MHz bandwidth of the GBT’s L-band receiver, a factor of more than 10 increase in what was possible with the previous generation high-precision pulsar backend at the GBT. If we used it in a week-long observing campaign, with observations of several hours each day, we predicted that the timing precision would increase by a factor of up to 10.

The 8-hour observation during conjunction was simply stunning. Hundreds of data points with \(\sim 1\mu s\) errors showed the extremely strong and cusp-like signature indicative of Shapiro delay from a nearly edge-on orbit. When the observing campaign was over, we measured the two parameters associated with the Shapiro delay to high precision, which in combination with the Keplerian orbital parameters, gave us the mass of the white dwarf \((0.500\pm0.006 M_\odot)\), the orbital inclination \((89.17\pm0.02\text{ degrees})\), and a pulsar mass of \(1.97\pm0.04 M_\odot\), by far the most massive precisely measured neutron star to date (Demorest et al. 2010). The GBT with GUPPI had turned a “vanilla” MSP into an important probe of high-density physics, which has strongly constrained the neutron star equation of state (i.e. EOS; Lattimer & Prakash 2010) and touched on many other aspects of both basic and astro-physics (e.g. Özel et al. 2010). It also made J1614−2230 into a timing array pulsar for the detection of gravitational waves.

5. Gravitational waves: the next frontier for MSPs?

Pulsar timing arrays (PTAs) have the potential to help revolutionize our view of the Universe, by giving us direct detections of gravitational waves (GWs), and maybe (just maybe) doing it before Advanced LIGO does. The idea of using pulsar timing to detect gravitational waves goes back to Detweiler (1979). The basic gist is that GWs with wavelengths of light-years, or consequently frequencies in the nanohertz regime, will stretch and compress the space-time through which radio pulses travel and thereby advance or

† https://safe.nrao.edu/wiki/bin/view/CICADA/NGHPP
delay their arrival times here at Earth. A problem, though, is that long-term changes in arrival times from a pulsar could be due to a variety of reasons, such as errors in our atomic time-standards or planetary ephemerides, or even simply timing noise from the pulsar itself. Hellings & Downs (1983) though, showed that the quadrupolar-nature of GWs leads to correlated delays in the arrival times from an array of pulsars, based on the angular separation of pairs of pulsars on the sky.

Where would these GWs come from? While it is possible that we could see “strong” GWs left over from Inflation or from the interaction of cosmic strings, most people believe our most likely sources of nanohertz GWs will come from supermassive ($10^8 - 10^9 M_\odot$) black hole binaries (SMBHBs) orbiting on years-long timescales before they coalesce. Such binary systems are thought to exist throughout the Universe as a result of galaxy mergers during hierarchical structure formation (e.g. Sesana 2012). These black hole binaries, even at distances of a Gpc, can cause perturbations of order 10 ns in pulsar timing residuals. If Nature was kind to us, the strongest of these sources (meaning a combination of the most massive and closest to us in the nanohertz frequency regime), will be detected individually. Such a detection could allow for localization on the sky, detection in other electro-magnetic wavebands, and might allow us to “calibrate” and improve our PTAs similar to the way that interferometers calibrate and “phase-up” on bright astrophysical point sources.

Even without a strong nearby individual source, though, we are likely to detect a steep-spectrum (i.e. much stronger at lower GW frequencies) stochastic background made up of the ensemble of all SMBHBs throughout the Universe (e.g. Hellings & Downs 1983), within the next 5–10 years. One of the great things about the stochastic background is that as we time the pulsars in our PTAs longer, and therefore to lower frequencies, our sensitivity increases not just by simply accumulating more data, but by climbing up the steep spectrum to where the GWs are stronger. This results in our sensitivities improving at a much faster rate than the naive $\sqrt{T}$. No matter what, the signal amplitudes will only be in the nanoseconds to tens of nanoseconds regime and so we need the best instrumentation and the best MSPs for our experiments.

Currently there are three major PTA efforts underway: NANOGrav, the North American Nanohertz Observatory for Gravitational Waves, which uses Arecibo and the GBT (Demorest et al. 2012); the European Pulsar Timing Array (EPTA), using several of Europe’s largest telescopes (van Haasteren et al. 2011); and the Parkes Pulsar Timing Array (PPTA), using the Parkes telescope in Australia (Manchester et al. 2012). Each of these efforts has been timing $\sim 15 – 30$ MSPs for the past 5–10 years with continually improving timing residuals, including several pulsars in the $50–100$ ns regime and many more at $100–300$ ns. In addition, there is an effort underway to combine the data from all three PTAs into the International Pulsar Timing Array (IPTA; Hobbs et al. 2010), which will improve the overall sensitivity by a factor of $\sim 2$ compared to any single PTA.

Despite the fact that PTA sensitivities are continuing to get better due to improvements in our timing techniques and our instrumentation, we still need more and better MSPs to fully achieve the potential of a pulsar-based GW “observatory”. That potential, and the possibility of an imminent GW detection by pulsar timing, is driving many large-scale efforts to find more MSPs.

6. New surveys for millisecond pulsars

The millisecond pulsar renaissance can most certainly be seen in the results of the recent and ongoing surveys for new pulsars. New instrumentation and increased compute capacity has dramatically improved MSP search sensitivities from the same telescopes
Figure 1. (Left) Number of known Galactic (i.e. not in globular clusters) millisecond pulsars (MSPs) as a function of year, through November 1, 2012. MSPs are defined here as recycled pulsars spinning faster than 15 ms. The rapidly increasing numbers of these systems are due primarily to new wide-area radio surveys using much improved instrumentation and Fermi’s ability to point us at likely radio MSPs. For up-to-date numbers, see Duncan Lorimer’s list at http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt (Right) Folded Fermi LAT gamma-ray photons of the 3.68 ms radio and gamma-ray binary MSP J1231-1411 (Ransom et al. 2011). The plot contains 3 yrs of Fermi data, corresponding to ~3000 photons (about 3 per day!), ~560 binary orbits, and 24 billion rotations of the pulsar, yet the main peak has a width of just over 2% of the pulse period — a beautiful example of the power of pulsar timing.

and even from the same radio receivers which have surveyed the sky before. The number of Galactic MSPs (i.e. those not in globular clusters, whose numbers have increased hugely as well) has doubled in the last three years and quadrupled in the last decade (see Figure 1). About half of those found in the past few years have come from a series of large-area surveys being conducted by the GBT (the GBT Driftscan and Green Bank North Celestial Cap or GBNCC surveys; Lynch et al., these procs.), Arecibo (Pulsar-ALFA and the AO327 Driftscan surveys; Lazarus et al., these procs.), and Parkes (the three related High Time Resolution Universe or HTRU surveys; Keith et al., these procs.).

These surveys are using either low-frequency (~350 MHz) receivers with short dwell times or higher-frequency systems (~1400 MHz) with multiple beams to increase survey speeds and enable them to cover large areas of the sky. When complete in the next couple years, the full sky will have been re-surveyed by one or more telescopes and the total data volume will approach 2 Petabytes. While the data-taking is not quite halfway complete, an even smaller fraction of the new data has been fully processed, ensuring that the discovery rate will continue for several years to come.

A fantastic short-cut to finding new MSPs has been provided by the Fermi satellite, though. Shortly after launch, Fermi showed that most MSPs are copious producers of pulsed gamma-ray emission (Abdo et al. 2009). That meant that many of the unassociated Fermi LAT sources, especially those well off of the Galactic plane, might be MSPs. A collaboration of radio astronomers working with the LAT team, called the Pulsar Search Collaboration, has uncovered at least 45 new radio MSPs (and counting!) by searching
these gamma-ray sources deeply with the biggest radio telescopes around the world (Ray et al. 2012). We would eventually find most of these MSPs with increasingly sensitive all-sky radio telescopes, but Fermi is showing us exactly where to look and allowing us to find them much sooner. Once radio timing solutions are established, basically all of them are seen to pulse in gamma-rays as well (see Figure 1), giving us a brand new probe into the pulsar magnetosphere and emission processes. A large fraction of the new Fermi MSPs are turning out to be previously rare eclipsing systems, a point we currently do not understand. Since there seems to be no strong correlation between the gamma-ray and radio fluxes, we expect that new Fermi-directed radio MSPs will be uncovered for as long as new Fermi sources are being detected.

Most pulsar surveys uncover one or two surprises, and in fact it is for these exotic systems that we often tune the parameters of our searches. High on the current “Most Wanted” list are a sub-millisecond pulsar, which would strongly constrain the EOS of neutron star matter, and a pulsar-black hole system, which would be an incredible testbed of strong-field general relativity (see Michael Kramer’s contribution to these proceedings). We don’t have those yet(?), but there have certainly been other recent surprises.

The GBT Driftscan survey uncovered a fast and bright MSP in a 4.75-hr orbit which, it turned out, had been studied as a likely accreting cataclysmic variable, in the optical, radio, and X-rays for the decade preceding its discovery as an MSP (Archibald et al. 2009). The pulsar, J1023+0038, seems to be a “Missing Link” system in the late stages of the recycling process as stellar evolution of the evolved companion nears completion. There are now a half dozen similar systems known, many uncovered with the help of Fermi, and all fascinating probes into binary and stellar evolution† (Roberts, these procs.).

Deep in the Galactic plane, the P-ALFA survey uncovered another evolutionary odd-ball, MSP J1903+0327, which is in an eccentric orbit around a Sun-like main-sequence star (Champion et al. 2008). This highly-inclined system can be timed quite precisely and has yielded Shapiro delay as well as the relativistic orbital precession of periastron, thereby providing a very precise, and fairly high, neutron star mass (1.667±0.021 $M_\odot$; Freire et al. 2011). The formation mechanism of the system is uncertain, but given that the star which spun up the pulsar is missing, a likely triple scenario involving a dynamical instability seems to be the best bet. Intriguingly, the GBT Driftscan survey has recently uncovered an MSP which is currently in a triple stellar system (Ransom et al. in prep.).

Finally, more pulsar planets, or at least planet-mass companions, have been uncovered in three new MSP systems, two of which were announced at this conference (see Bates et al. and Lynch et al.). The first of these is the so-called “Diamond Planet” system J1719−1438, with a Jupiter-mass companion in a compact 2.2-hr binary (Bailes et al. 2011). The density of the companion is constrained to be very large, implying that it is an ultra-low mass carbon white dwarf in crystalline form (i.e. diamond!). Pulsar timing can easily detect planets of almost any reasonable mass, so it is interesting to ask why are there so few pulsar planets?

7. Prospects for the future

With pulsar instrumentation approaching perfection and several large surveys underway and already successful, it is easy to predict good things from pulsars, and in particular MSPs, in the coming few years. We will eke out additional timing precision from our instruments and techniques which will lead to more surprises, and potentially on short timescales — more planets? more massive or maybe low-mass neutron stars? grav-

† These systems have been coined “Redbacks” in spider-salute to the “Black Widow” pulsars.
itational waves? And all-sky or targeted surveys could uncover a new “Holy Grail” any
day, an eccentric MSP-MSP binary could lurk in a globular cluster, and SgrA* should
be surrounded by hundreds of pulsars.

Unfortunately, though, there are some issues. Nearly all of the “classic” pulsar tele-
scopes, Arecibo, Jodrell Bank’s Lovell Telescope, Parkes, and now the GBT, have recently
been or are currently under serious threat of closure due to dwindling or changing bud-
gets. “Simple” single-dish radio telescopes can do fantastic things for pulsar astronomy,
but they are being eclipsed by current and next-generation radio arrays which promise
to do more things for more astronomers. Great pulsar astronomy will certainly be done
with upcoming arrays like MeerKAT, LOFAR, and the Phase I SKA, but things are
trickier and potentially costlier with arrays. It will be important to carefully weigh the
costs of closing simple single-dish telescopes, which can be very effective at producing
high-impact pulsar science, as we march towards the era of giant radio arrays.

China’s upcoming 500-m diameter single-dish called FAST will be an excellent test case
(Li et al., these procs.). Its incredible sensitivity and increased sky coverage compared to
Arecibo could revolutionize pulsar astronomy before the Phase I SKA is even partially
complete. No matter what, if and when these giant new facilities come on line, some
of the first and best science you will see will be from pulsars. How could it not? These
things are wicked cool. Seriously.

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Magnetars: neutron stars with huge magnetic storms

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Abstract. Among the many different classes of stellar objects, neutron stars provide a unique environment where we can test (at the same time) our understanding of matter with extreme density, temperature, and magnetic field. In particular, the properties of matter under the influence of magnetic fields and the role of electromagnetism in physical processes are key areas of research in physics. However, despite decades of research, our limited knowledge on the physics of strong magnetic fields is clear: we only need to note that the strongest steady magnetic field achieved in terrestrial labs is some millions of Gauss, only thousands of times stronger than a common refrigerator magnet. In this general context, I will review here the state of the art of our research on the most magnetic objects in the Universe, a small sample of neutron stars called magnetars. The study of the large high-energy emission, and the flares from these strongly magnetized (∼10^{15} Gauss) neutron stars is providing crucial information about the physics involved at these extremes conditions, and favoring us with many unexpected surprises.

Keywords. stars: neutron, X-rays: stars, stars: magnetic fields, stars: flare, dense matter, methods: data analysis

1. Introduction

Neutron stars are the debris of the supernova explosion of massive stars, the existence of which was first theoretically predicted around 1930 (Chandrasekhar 1931; Baade & Zwicky 1934) and then observed for the first time more than 30 years later (Hewish et al. 1968). They were predicted all along as very dense and degenerate stars holding about 1.4 solar masses in a sphere of 10km radius. We now know many different flavors of these compact objects, and many open questions are still waiting for an answer after decades of studies. The neutron star population is dominated by radio pulsars (thousands of objects), however in the last decades several extreme and puzzling sub-classes of isolated neutron stars were discovered: Anomalous X-ray Pulsars (AXPs), Soft Gamma Repeaters (SGRs; see Mereghetti 2008), Rotating Radio Transients (RRATs; Keane & McLaughlin 2011), X-ray Dim Isolated Neutron stars (XDINSs; Turolla 2009), and Central Compact Objects (CCOs; Mereghetti 2011). The large amount of different acronyms might already show how diverse is the neutron star class, and on the other hand, how far we are from a unified scenario. These objects are amongst the most intriguing populations in modern high-energy astrophysics and in physics in general. They are precious places to test gravitational and particle physics, relativistic plasma theories, as well as strange quark states of matter and physics of atoms and molecules embedded in extremely high magnetic fields (impossible to be reproduced on Earth). Since their discovery in the late sixties, about 2000 rotational powered pulsars are known to date, thanks to numerous surveys using single dish radio antennas around the world (Parkes, Green Bank, Jodrell Bank, Arecibo), with periods ranging from about 1.5 ms to 12 s (see Figure 4, and the
Figure 1. Artistic image of the magnetic field of a magnetar close to its surface (Rea et al. 2012; published in Science as Editors’ choice).

ATNF on-line catalog: Manchester et al. 2005), and they have magnetic fields ranging between $\sim 10^{10} - 10^{15}$ Gauss. The energy reservoir of all those pulsars is well established to be their rapid rotation, having a rotational luminosity $L_{\text{rot}} \sim 4\pi^2 I \dot{P}/P^3 \sim 3.9 \times 10^{46} \dot{P}/P^3 \text{ erg/s}$. A key ingredient to activate the radio emission is the acceleration of charged particles, which are extracted from the star’s surface by an electrical voltage gap. The voltage gap forms due to the presence of a dipolar magnetic field co-rotating with the pulsar, and it is believed to extend up to an altitude of $\sim 10^4$ cm with a potential difference $> 10^{10}$ statvolts. Primary charges are accelerated by the electric field along the magnetic field lines to relativistic speeds and emit curvature radiation. Curvature photons are then converted into electron-positron pairs and this eventually leads to a pair cascade which is ultimately responsible for the coherent radio emission we observe from radio pulsars. Very energetic pulsars are also observed until the gamma-ray range, most probably in the form of synchrotron photons coming from the acceleration in the so-called ’outer-gap’ of the pulsar magnetosphere (Goldreich & Julian 1969; Ruderman & Sutherland 1975). All isolated pulsar rotational periods are increasing in time. This spin down is quantified by the braking index, $n = \Omega \dddot{\Omega}/\dot{\Omega}^2$ (where $\Omega = 1/P$). With this definition, under the assumption of pure dipole braking, we would expect all pulsars having $n = 3$.

In this review we will report on the state of the art of the study of the strongest magnets in the Universe: the magnetars. However, before presenting these ultra-magnetic objects, it is instructive to indicate how the magnetic field of isolated pulsars is commonly estimated. Assuming that pulsars slow down due to magnetic dipole radiation, the surface dipolar magnetic field ($B_{\text{dip}}$) can be estimated from the measured pulsar spin period $P$ and its first derivative $\dot{P}$: $B_{\text{dip}} \sim 3.2 \times 10^{19} \sqrt{PP}$ Gauss (where $P$ is in units of seconds).
The ‘magnetars’ (comprising AXPs and SGRs; Mereghetti 2008) are a small group of X-ray pulsars (about twenty objects with spin periods between 2–12 s) the emission of which is very hard to explain by any of the scenarios for the radio pulsar or the accreting X-ray binary populations. In fact, the very strong X-ray emission of these objects ($L_x \sim 10^{35}$ erg/s) seemed too high and variable to be fed by the rotational energy alone (as in the radio pulsars), and no evidence for a companion star has been found so far in favor of any accretion process (as in the X-ray binary systems). Moreover, roughly assuming them being magnetic dipole radiator, their inferred magnetic fields appear to be as high as $B_{\text{dip}} \sim 10^{14} - 10^{15}$ Gauss. They are then higher than the electron critical magnetic field, $B_Q = m_e^2 c^3 / e h \sim 4.4 \times 10^{13}$ G at which an electron gyro-rotating around such magnetic field line gains a cyclotron energy equal to its rest mass. At fields higher than $B_Q$, QED effects such as vacuum polarization or photon splitting, can take place (see Harding & Lai 2006).

Because of these high B fields, the emission of magnetars was thought to be powered by the decay and the instability of their strong fields (Duncan & Thompson 1992; Thompson & Duncan 1993, 1995). This powerful X-ray output is usually well modeled by a thermal emission from the neutron star hot surface (about $3 \times 10^6$ Kelvin) reprocessed in a twisted magnetosphere through resonant cyclotron scattering, a process favored only under these extreme magnetic conditions (Thompson, Lyutikov & Kulkarni 2002; Nobili, Turolla & Zane 2008; Rea et al. 2008; see Figure 1 for an artistic representation of a magnetar).
On top of their persistent X-ray emission, magnetars emit very peculiar flares on short timescales (from fraction to hundreds of seconds) emitting a large amount of energy ($10^{40} - 10^{46}$ erg; the most energetic Galactic events after the supernova explosions). They are probably caused by large scale rearrangements of the surface/magnetospheric field, either accompanied or triggered by fracturing of the neutron-star crust, as a sort of stellar quakes. Furthermore, magnetars also show large outbursts where their steady emission can be enhanced up to $\sim$1000 times its quiescent level (see Figure 2, and see Rea & Esposito 2010 for recent review on transient magnetars). From the few well-monitored events, we are starting to understand how those outbursts are produced. They are caused by similar crustal fractures as the shorter flares, accompanied by strong surface heating, and often by the appearance of additional hot spots on the neutron-star surface. This is what may cause large spectral changes during outbursts, pulse profile variability, and different cooling patterns depending on the outburst. We have recently started to model that outburst decay, and much important physical information is slowly emerging, i.e. that all outbursts saturate at $\sim 10^{36}$ erg/s, due to neutrino cooling processes, and regardless the source quiescent level. This discovery makes magnetar outbursts potential standard candles (Pons & Rea 2012; see Figure 3).

2. Hints for the connection between magnetars and radio pulsars

In the past few years, new discoveries started to shed light on a possible connection between magnetars and the typical radio pulsar population, weakening the strong distinction between these two classes, while pointing to a continuum of magnetar-like emission in the neutron star population. Below we list a few of those key discoveries.

- Magnetars were believed to be radio-quiet sources for a few decades. This was interpreted as the result of a photon splitting process that is very efficient in magnetic fields stronger than the critical electron field ($B_{Q}$; Baring 1998). The discovery in 2004 of transient magnetars coincided also with the discovery of radio pulsed emission from such sources (Camilo et al 2006; Levin et al. 2010). Magnetar pulsed radio emission, however, appeared to have different properties with respect to normal radio pulsars (flat radio

Figure 3. Left: Luminosity vs. time after energy injection. The models correspond to $E_{inj} = 1.7 \times 10^{41}$ erg, (solid line), $1.7 \times 10^{42}$ erg (dotted line), $1.7 \times 10^{43}$ erg (dashed line), and $1.7 \times 10^{44}$ erg (dash-dotted line). Right: quiescent luminosity vs. outburst maximum flux increase (all in the 1-10 keV band), for all magnetars showing bursts, glitches or outbursts. See Pons & Rea 2012 for further details.
spectra, large variability, connection with X-ray outbursts). This came as a big surprise, and started the idea of a possible connection between magnetars and the typical radio pulsars. Furthermore, recently a study of radio magnetars showed that despite the different characteristics, the radio emission can have the same physical mechanisms as for rotation-powered pulsars (Rea et al. 2012): powered by rotational energy (see also Figure 5), but with different observational properties possibly caused by a different path that a pair cascade might undertake when embedded in a mostly toroidal magnetic field.

- Deep radio surveys discovered a few radio pulsars having dipolar fields larger than the $B_Q$ (see Figure 4). Although having magnetic fields in the magnetar range those objects were behaving as normal radio pulsars, and this was interpreted by a different magnetic geometry between the two classes. In 2008, bursting activity and an X-ray outburst were detected from a high-B pulsar, showing the presence of magnetar-like activity (Gavriil et al. 2008; Kumar & Safi-Harb 2008).

- The extensive follow-up of transient magnetars undergoing an outburst had allowed the most unexpected discoveries. In particular, prompted by detection of typical magnetar-like bursts and a powerful outburst of the persistent emission, a new transient magnetar was discovered in 2009, namely SGR 0418+5729. However, with great surprise after more than a year of extensive monitoring, no period derivative was detected, which led to an upper limit on the source surface dipolar field of $B_{dip} < 7.5 \times 10^{12}$ Gauss (Rea et al. 2010). For the first time we witnessed a magnetar with a low dipolar magnetic
Figure 5. X-ray luminosity versus the spin-down luminosity for all pulsars having a detected X-ray emission (grey filled circles), high-B pulsars (filled triangle), and the magnetars (red stars). Grey shaded circles mark the magnetars and high-B pulsars with detected pulsed radio emission, and the solid line shows \( L_x = L_{\text{rot}} \). X-ray luminosities are calculated in the 0.5–10 keV energy range, and for variable sources refer to the quiescent emission state.

field. This discovery demonstrated that not only a critical magnetic field (> \( B_Q \)) was not necessary to have magnetar-like activity, but many 'apparently' normal pulsars can turn out as magnetars at anytime (in fact the discovery of a second low-B magnetar soon followed; Rea et al. 2012; Scholz et al. 2012; see also Figure 4).

• Advances in the measurement of pulsar breaking indexes showed the existence of objects with indexes \( n \) smaller than 3, which would imply an increasing magnetic field with age under the common magnetic breaking picture. In particular this is the case of the high-B pulsar PSR 1734-33 (Espinoza et al. 2011), discovered to have \( n = 0.9 \). This discovery favors models for which the magnetic field is buried into the crust by accretion in the first supernova phases, and start re-emerging during the pulsar life-time (Viganó & Pons 2012). A similar conclusion has been reached with the discovery of low-B fields in CCOs, whose young age and hot surface temperature are instead pointing to a strong buried magnetic field, despite what measured by their period and period derivatives (Halpern et al. 2007).

3. Conclusions

The above discoveries, among others, re-focus the attention on a few important ingredients of neutron star physics: i) the surface dipolar magnetic field strength cannot be the only parameter driving their magnetar or radio pulsar nature, ii) magnetars can behave
as radio pulsars and vice-versa, possibly powered by a similar mechanism sustained by rotational energy, and iii) an internal strong magnetic field is required to explain the low braking indexes of a few radio pulsars, as well as the emission of the compact central objects, despite the rather low dipolar magnetic field component.

These discoveries show that extremely strong magnetic fields may be very common among the pulsar population, rather than an exception. This might imply that supernova explosions should be generally able to produce such strong magnetic fields, hence that most massive stars are either producing fast rotating cores during the explosion to activate the dynamo, or are strongly magnetized themselves (i.e. 1 kGauss at least). Furthermore, in this scenario several gamma-ray bursts (not only an irrelevant fraction), might indeed be due to the formation of magnetars, and the gravitational wave background produced by magnetar formation should then be larger than predicted so far (important for future instruments as Advanced-LIGO).

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Probing gravitation with pulsars

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Abstract. Radio pulsars are fascinating and extremely useful objects. Despite our on-going difficulties in understanding the details of their emission physics, they can be used as precise cosmic clocks in a wide-range of experiments – in particular for probing gravitational physics. While the reader should consult the contributions to these proceedings to learn more about this exciting field of discovering, exploiting and understanding pulsars, we will concentrate here on the usage of pulsars as gravity labs.

Keywords. gravitation, techniques:radio astronomy, stars:neutron, pulsars:general

1. Introduction

We are less than three years away from celebrating the centenary of Einstein's theory of general relativity (GR). Nearly a hundred years later, efforts in testing GR and its concepts are still being made by many colleagues around the world, using many different approaches. To date GR has passed all experimental and observational tests with flying colours, but in light of recent progress in observational cosmology in particular, the question of as to whether alternative theories of gravity need to be considered is as topical as ever.

Many experiments are designed to achieve ever more stringent tests by either increasing the precision of the tests or by testing different, new aspects. Some of the most stringent tests are obtained by satellite experiments in the solar system, providing exciting limits on the validity of GR and alternative theories of gravity. However, solar-system experiments are made in the gravitational weak-field regime, while deviations from GR may appear only in strong gravitational fields.

We are all very much looking forward to the first direct detection of gravitational waves with ground-based (and hopefully, eventually, space-based) detectors, which not only open a completely new window to the Universe but which will also provide superb tests of GR. Meanwhile, it happens that nature provides us with an almost perfect laboratory to test the strong-field regime - in the form of binary radio pulsars.

While, strictly speaking, the binary pulsars move in the weak gravitational field of a companion, they do provide precision tests of the strong-field regime. This becomes clear when considering that the majority of alternative theories predicts strong self-field effects which would clearly affect the pulsars' orbital motion. By ”simply” measuring the arrival time of pulsars moving in the curved space-time of their companion, we can locate their position in their orbit with an uncertainty as little as 20-50 m! Hence, tracing their fall in a gravitational potential, we can search for tiny deviations from GR, providing us with unique precision strong-field tests of gravity.
2. Simple and clean experiments

The use of pulsars for tests of gravitational physics with “pulsar timing” is a clean and conceptually simple experiment. By simply measuring the exact arrival time of pulses at our telescope on Earth, we do a ranging experiment that is vastly superior in precision than a simple measurement of Doppler-shifts in the pulse period. In fact, the pulsed nature of our signal that links tightly and directly to the rotation of the neutron star, allows us to count every single rotation of a neutron star (see contribution by Scott Ransom for details). In this experiment we can consider the pulsar as a test mass that has a precision clock attached to it and which allows us to follow the movement of the test mass in the curved space-time of the companion. As a result, a wide range of relativistic effects can be observed, identified and studied. These include so far:

- Precession of periastron
- Gravitational redshift
- Shapiro delay due to curved space-time
- Gravitational wave emission
- Geodetic precession, relativistic spin-orbit coupling
- Speed of gravity

But we can also convert our observations in the tests of concepts and principles deeply embedded in theoretical frameworks, such as

- Strong Equivalence Principle (grav. Stark effect),
- Lorentz invariance of gravitational interaction,
- Non-existence of preferred frames,
- Conservation of total momentum,
- Non-variation of gravitational constant,

which also leads to stringent limits on alternatives theories of gravity, e.g. tensor–scalar theories, Tensor-Vector-Scalar (TeVeS) theories.

2.1. Pick your laboratory!

The various effects or concepts to be tested require sometimes a rather different type of laboratory. For instance, to test the violation of the Strong-Equivalence-Principle, one would like to use a binary system that consists of different types of masses (i.e. with different gravitational self-energy), rather than a system made of very similar bodies. Fortunately, nature has been kind.

At the moment, we know about 2000 pulsars, with about 10% of these in binary systems. The shortest orbital period is about 90 min while the longest period is 5.3 yr (e.g. Lorimer & Kramer 2005). We find different types of components, i.e. main-sequence stars, white dwarfs (WD), neutron stars (NS) and even planets. Unfortunately, despite past and on-going efforts, we have not yet found a pulsar about a stellar black hole companion or about the supermassive black hole in the centre of our Galaxy (Liu et al. 2012). Double neutron star systems are rare but usually produce the largest observable relativistic effects in their orbital motion and, as we will see, produce the best tests of general relativity for strongly self-gravitating bodies. In comparison, pulsar - white dwarf systems are much more common. Indeed, most pulsar companions are white dwarfs, with a wide range of orbital periods, ranging from hours to days, weeks and months. Still, many of them can be used for tests of gravitational theories where we utilize the fact that white dwarfs and neutron stars differ very significantly in their structure and, consequently, self-energies.
Table 1. Examples of precision measurements using pulsar timing as a demonstration what is possible today. The digit in bracket indicates the uncertainty in the last digit of each value. References are cited. More details on gravitational wave detection with pulsar timing arrays can be found in the contributions by Hobbs, Liu, Shannon and others.

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<th>Orbital parameters:</th>
<th>Astrometry:</th>
<th>Tests of general relativity:</th>
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2.2. Not only clean, but also very precise

We follow the pulsars in their orbit by registering the variation in arrival time as they move around the system’s centre of mass. Using pulsar timing techniques, we make extremely precise measurements that allow us to probe gravitation with exquisite accuracy. Table 1 gives an idea about the precision that we already achieve today. With future telescopes like the “Square Kilometre Array”, the precision will even be enhanced by at least two orders of magnitudes and should, for instance, allow us to find a pulsar orbiting SGR A*, which would provide the mass of the central black hole to a precision of an amazing $1 M_\odot$! It would also allow us to measure the spin of the black hole with a precision of $10^{-4}$ to $10^{-3}$ (enabling tests of the “cosmic censorship conjecture”) and the quadrupole moment with a precision to $10^{-4}$ to $10^{-3}$ (thus enabling tests of the “no-hair theorem”). See Liu et al. (2012) and the contribution by Wex et al. for more details.

3. The first laboratory

The first binary pulsar to ever be discovered happenped to be a rare double neutron star system. It was discovered by Russel Hulse and Joe Taylor in 1974 (Hulse & Taylor 1975). The pulsar, B1913+16, has a period of 59 ms and is in eccentric ($e = 0.61$) orbit around an unseen companion with an orbital period of less than 8 hours. It became soon clear that the pulsar does not follow the movement expected from a simple Keplerian description of the binary orbit, but that it shows the impact of relativistic effects. In order to describe the relativistic effects in a theory-independent fashion, one introduces so-called “Post-Keplerian” (PK) parameters that are included in a timing model to accurately describe the measured pulse times-of-arrival (see e.g. contribution by David Nice for more details).
For the Hulse-Taylor pulsar, it was soon measured that the system showed a relativistic advance of its periastron, comparable to what is seen in the solar system for Mercury, albeit with a much larger amplitude of \( \dot{\omega} = 4.226598 \pm 0.000005 \text{ deg/yr} \) (Weisberg et al. 2010). GR predicts a value for the periastron advance that depends on the Keplerian parameters and the masses of the pulsar and its companion:

\[
\dot{\omega} = 3T_\odot^{2/3} \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{1 - e^2} \left( m_p + m_c \right)^{2/3}.
\] (3.1)

Here, \( T_\odot \) is a constant, \( P_b \) the orbital period, \( e \) the eccentricity, and \( m_p \) and \( m_c \) the masses of the pulsar and its companion. See Lorimer & Kramer (2005) for further details.

The Hulse-Taylor pulsars also shows the effects of gravitational redshift (including a contribution from a second-order Doppler effect) as the pulsar moves in its elliptical orbit at varying distances from the companion and with varying speeds. The result is a variation in the clock rate of with an amplitude of \( \gamma = 4.2992 \pm 0.0008 \text{ ms} \) (Weisberg et al. 2010). In GR, the observed value is related to the Keplerian parameters and the masses as

\[
\gamma = T_\odot^{2/3} \left( \frac{P_b}{2\pi} \right)^{1/3} \frac{m_c(m_p + 2m_c)}{(m_p + m_c)^{4/3}} \] (3.2)

We can now combine these measurements. We have two equations with a measured left-hand side. On the right-hand side, we measured everything apart from two unknown masses. We solve for those and obtain, \( m_p = 1.4398 \pm 0.0002 \, M_\odot \) and \( m_c = 1.3886 \pm 0.0002 \, M_\odot \) (Weisberg et al. 2010). These masses are correct if GR is the right theory of gravity. If that is indeed the case, we can make use of the fact that (for point masses with negligible spin contributions), the PK parameters in each theory should only be functions of the a priori unknown masses of pulsar and companion, \( m_p \) and \( m_c \), and the easily measurable Keplerian parameters (Damour & Taylor 1992). With the two masses now being determined using GR, we can compare any observed value of a third PK parameter with the predicted value. A third such parameter is the observed decay of the orbit which can be explained fully by the emission of gravitational waves. And indeed, using the derived masses, and the prediction of general relativity, i.e.

\[
\dot{P}_b = -\frac{192\pi}{5} T_\odot^{5/3} \left( \frac{P_b}{2\pi} \right)^{-5/3} \left( \frac{1 + \frac{73}{72}e^2 + \frac{37}{36}e^4}{(1-e^2)^{7/2}} \right) \frac{m_p m_c}{(m_p + m_c)^{1/3}},
\] (3.3)

one finds an agreement with the observed value of \( \dot{P}_{b\text{obs}} = (2.423 \pm 0.001) \times 10^{-12} \) (Weisberg et al. 2010) – however, only if a correction for a relative acceleration between the pulsar and the solar system barycentre is taken into account. As the pulsar is located about 7 kpc away from Earth, it experiences a different acceleration in the Galactic gravitational potential than the solar system (see e.g. Lorimer & Kramer 2005). The precision of our knowledge to correct for this effect eventually limits our ability to compare the GR prediction to the observed value. Nevertheless, the agreement of observations and prediction, today within a 0.2\% (systematic) uncertainty (Weisberg et al. 2010), represented the first evidence for the existence of gravitational waves. Today we know many more binary pulsars where we can detect gravitational wave emission. In one particular case, the measurement uncertainties are not only more precise, but also the systematic uncertainties are much smaller, as the system is much more nearby. This system is the Double Pulsar.

† For alternative theories of gravity this statement may only be true for a given equation-of-state.
4. The Double Pulsar

The Double Pulsar was discovered in 2003 (Burgay et al. 2003, Lyne et al. 2004). It does not only show larger relativistic effects and is much closer to Earth (about 1 kpc) than the Hulse-Taylor pulsar, allowing us to largely neglect the relative acceleration effects, but the defining unique property of the system is that it does not consist of one active pulsar and its unseen companion, but that it harbours two active radio pulsars.

One pulsar is mildly recycled with a period of 22 ms (named “A”), while the other pulsar is young with a period of 2.8 s (named “B”). Both orbit the common centre of mass in only 147-min with orbital velocities of 1 Million km per hour. Being also mildly eccentric ($e = 0.09$), the system is an ideal laboratory to study gravitational physics and fundamental physics in general. A detailed account of the exploitation for gravitational physics has been given, for instance, by Kramer et al. (2006), Kramer & Stairs (2008) and Kramer & Wex (2009). An update on those results is in preparation (Kramer et al., in prep.), with the largest improvement undoubtedly given by a large increase in precision when measuring the orbital decay. Not even ten years after the discovery of the system, the Double Pulsar provides the best test for the accuracy of the gravitational quadrupole emission prediction by GR far below the 0.1% level.

In order to perform this test, we first determine the mass ratio of pulsar A and B from their relative sizes of the orbit, i.e. $R = x_A / x_B = m_A / m_B = 1.0714 \pm 0.0011$ (Kramer et al. 2006). Note that this value is theory-independent to the 1PN level (Damour & Deruelle 1986). The most precise PK parameter that can be measured is a large orbital precession, i.e. $\dot{\omega} = 16.8991 \pm 0.0001$ deg/yr. Using Eq. (3.1), this measured value and the mass ratio, we can determine the masses of the pulsars, assuming GR is correct, to be $m_A = (1.3381 \pm 0.0007) M_\odot$ and $m_B = (1.2489 \pm 0.0007) M_\odot$.

We can use these masses to compute the expected amplitude for the gravitational redshift, $\gamma$, if GR is correct. Comparing the result with the observed value of $\gamma = 383.9 \pm 0.6 \mu$s, we find that theory (GR) agrees with the observed value to a ratio of $1.000 \pm 0.002$, as a first of five tests of GR in the Double Pulsar.

The Double Pulsar also has the interesting feature that the orbit is seen nearly exactly edge-on. This leads to a 30-s long eclipse of pulsar A due to the blocking magnetosphere of B that we discuss further below, but it also leads to a “Shapiro delay”: whenever the pulse needs to propagate through curved space-time, it takes a little longer than travelling through flat space-time. At superior conjunction, when the signal of pulsar A passes the surface of B in only 20,000km distance, the extra path length due to the curvature of space-time around B leads to an extra time delay of about $100 \mu$s. The shape and amplitude of the corresponding Shapiro delay curve yield two PK parameters, $s$ and $r$, known as shape and range, allowing two further tests of GR. $s$ is measured to $s = \sin(i) = 0.99975 \pm 0.00009$ and is in agreement with the GR prediction of

$$s = T_\odot^{-1/3} \left( \frac{P}{2\pi} \right)^{-2/3} \frac{x (m_A + m_B)^{2/3}}{m_B},$$

(4.1)

(where $x$ is the projected size of the semi-major axis measured in lt-s) within a ratio of $1.0000 \pm 0.0005$. It corresponds to an orbital inclination angle of $88.7 \pm 0.2$ deg, which is indeed very close to $90$ deg as suggested by the eclipses. $r$ can be measured with much less precision and yields an agreement with GR’s value given by

$$r = T_\odot m_B,$$

(4.2)

to within a factor of $0.98 \pm 0.02$.

A fourth test is given by comparing an observed orbital decay of $107.79 \pm 0.11 \text{ ns/day to}$
the GR prediction. Unlike the Hulse-Taylor pulsar, extrinsic effects are negligible and the values agree with each other without correction to within a ratio of $1.000 \pm 0.001$. This is already a better test for the existence of GW than possible with the Hulse-Taylor pulsar and will continue to improve with time. Indeed, at the time of writing the agreement has already surpassed the 0.1% level significantly (Kramer et al., in prep.).

5. Relativistic spin-orbit coupling

Apart from the Shapiro-delay, the impact of curved space-time is also immediately measurable by its effect on the orientation of the pulsar spin in a gyroscope experiment. This effect, known as geodetic precession or de Sitter precession represents the effect on a vector carried along with an orbiting body such that the vector points in a different direction from its starting point (relative to a distant observer) after a full orbit around the central object. Experimental verification has been achieved by precision tests in the solar system, e.g. by Lunar Laser Ranging (LLR) measurements, or recently by measurements with the Gravity Probe-B satellite mission (see Will 2006 for a review of experimental tests). However, these tests are done in the weak field conditions of the solar system, so that pulsars provide the only access to the strong-field regime.

In binary systems one can interpret the observations, depending on the reference frame, as a mixture of different contributions to relativistic spin-orbit interaction. One contribution comes from the motion of the first body around the centre of mass of the system (deSitter-Fokker precession), while the other comes from the dragging of the internal frame at the first body due to the translational motion of the companion (Börner et al. 1975). Hence, even though we loosely talk about geodetic precession, the result of the spin-orbit coupling for binary pulsar is more general, and hence we will call it relativistic spin-precession. The consequence of relativistic spin-precession is a precession of the pulsar spin about the total angular momentum vector, changing the orientation of the pulsar relative to Earth.

Since the orbital angular momentum is much larger than the angular momentum of the pulsar, the orbital spin practically represents a fixed direction in space, defined by the orbital plane of the binary system. Therefore, if the spin vector of the pulsar is misaligned with the orbital spin, relativistic spin-precession leads to a change in viewing geometry, as the pulsar precesses about the total angular momentum vector. Consequently, as many of the observed pulsar properties are determined by the relative orientation of the pulsar axes towards the distant observer on Earth, we should expect a modulation in the measured pulse profile properties, namely its shape and polarisation characteristics (Damour & Ruffini 1974). The precession rate is another PK parameter and given in GR by (e.g. Lorimer & Kramer 2005)

$$\Omega_p = T_\odot^{2/3} \times \left( \frac{2\pi}{P_b} \right)^{5/3} \times \frac{m_c(4m_p + 3m_c)}{2(m_p + m_c)^{4/3}} \times \frac{1}{1 - e^2}$$

(5.1)

In order to see a measurable effect in any binary pulsar, a) the spin axis of the pulsar needs to be misaligned with the total angular momentum vector and b) the precession rate must be sufficiently large compared to the available observing time to detect a change in the emission properties. Table 2 lists the known Double Neutron Star Systems which typically show the largest degree of relativistic effects due to the often short eccentric binary orbits. However, the last entry in the table is PSR J1141–6545 which is a relativistic system with a white dwarf companion. Those pulsars that are marked with an asterisk have been identified as pulsars showing relativistic spin precession. Note that the top 5 out of 8 sources (with a known expected precession rate) indeed show the effect.
As the most relativistic binary system known to date, we expect a large amount of spin precession in the Double Pulsar system. Despite careful studies, profile changes for A have not been detected, suggesting that A’s misalignment angle is rather small (e.g. Ferdman et al. 2012). In contrast, changes in the light curve and pulse shape on secular timescales (Burgay et al. 2005) reveal that this is not the case for B. In fact, B had been becoming progressively weaker and disappeared from our view in 2009 (Perera et al. 2010). Making the valid assumption that this disappearance is solely caused by relativistic spin precession, it will only be out of sight temporarily until it reappears later. Modelling suggests that, depending on the beam shape, this will occur in about 2035 but an earlier time cannot be excluded. The geometry that is derived from this modelling is consistent with the results from complementary observations of spin precession, visible via a rather unexpected effect described in the following.

The change on the orientation of B also changes the observed eclipse pattern in the Double Pulsar, where we can see periodic bursts of emission of A during the dark eclipse phases, with the period being the full- or half-period of B. As this pattern is caused by the rotation of B’s blocking magnetospheric torus that allows light to pass B when the torus rotates to be seen from the side, the resulting pattern is determined by the three-dimensional orientation of the torus, which is centred on the precessing pulsar spin. Eclipse monitoring over the course of several years shows exactly the expected changes, allowing to determine the precession rate to $\Omega_{p,B} = 4.77^{+0.66}_{-0.65}$ deg/yr. This value is fully consistent with the value expected GR, providing a fifth test (Breton et al. 2008). This measurement also allows to test alternative theories of gravity and their prediction for relativistic spin-precession in strongly self-gravitating bodies for the first time (see Kramer & Wex 2009 for details).

6. Alternative theories

Despite the successes of GR, a range of observational data have fuelled the continuous development of alternative theories of gravity. Such data include the apparent observation of “dark matter” or the cosmological results interpreted in the form of “inflation” and “dark energy”. Confronting alternative theories with data also in other areas of the parameter space (away from the CMB or Galactic scales), requires that these theories are developed sufficiently in order to make predictions. A particular sensitive criterion is if the theory is able to make a statement about the existence and type of gravitational waves. Most theories cannot (yet), but a class of theories where this has been achieved is the class of tensor-scalar theories as discussed and demonstrated by Damour and Esposito-Farèse in a series of works (e.g. Damour & Esposito-Farèse 1996). For corresponding tests, the choice of a double neutron star system is not ideal, as the difference in scalar change, (that would be relevant, for instance, for the emission of gravitational dipole radiation) is small. The ideal laboratory would be a pulsar orbiting a black hole, as the black hole would have zero scalar charge and the difference would be maximised. The next best laboratory is a pulsar-white dwarf system. Indeed, such binary systems are able to provide constraints for alternative theories of gravity that are equally good or even better than solar system limits (Freire et al. 2012).

7. Summary & Conclusions

A variety of experiments and observational data exist that allow us to test our understanding of gravity with increased precision. So far, general relativity has passed all tests with flying colours but the apparent existence of “Dark Energy” challenges this simple
Table 2. DNSs sorted according to the expected relativistic spin precession rate. Also included is PSR J1141−6545 which is in a relativistic orbit about a white dwarf companion. Pulsars marked with an asterisk have been identified of showing spin precession. For sources where no precession rate is listed, the companion mass could not be accurately measured yet, indicating however, that the precession rate is low.

<table>
<thead>
<tr>
<th>PSR</th>
<th>( P_{\text{ms}} )</th>
<th>( P_{\text{b}} ) (d)</th>
<th>( x ) (lt-s)</th>
<th>( e )</th>
<th>( \Omega_p ) (deg yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0737−3039A/B(^*)</td>
<td>22.7/2770</td>
<td>0.10</td>
<td>1.42/1.51</td>
<td>0.09</td>
<td>4.8/5.1</td>
</tr>
<tr>
<td>J1906+0746(^*)</td>
<td>144.1</td>
<td>0.17</td>
<td>1.42</td>
<td>0.09</td>
<td>2.2</td>
</tr>
<tr>
<td>B2127+11C(^*)</td>
<td>30.5</td>
<td>0.34</td>
<td>2.52</td>
<td>0.68</td>
<td>1.9</td>
</tr>
<tr>
<td>B1913+16(^*)</td>
<td>59.0</td>
<td>0.33</td>
<td>2.34</td>
<td>0.62</td>
<td>1.2</td>
</tr>
<tr>
<td>J1756−2251</td>
<td>28.5</td>
<td>0.32</td>
<td>2.76</td>
<td>0.18</td>
<td>0.8</td>
</tr>
<tr>
<td>B1534+12(^*)</td>
<td>37.9</td>
<td>0.42</td>
<td>3.73</td>
<td>0.27</td>
<td>0.5</td>
</tr>
<tr>
<td>J1829+2456</td>
<td>41.0</td>
<td>1.18</td>
<td>7.24</td>
<td>0.14</td>
<td>0.08</td>
</tr>
<tr>
<td>J1518+4904</td>
<td>40.9</td>
<td>8.64</td>
<td>20.0</td>
<td>0.25</td>
<td>–</td>
</tr>
<tr>
<td>J1753−2240</td>
<td>95.1</td>
<td>13.63</td>
<td>18.1</td>
<td>0.30</td>
<td>–</td>
</tr>
<tr>
<td>J1811−1736</td>
<td>104.2</td>
<td>18.8</td>
<td>34.8</td>
<td>0.83</td>
<td>–</td>
</tr>
<tr>
<td>J1141−6545(^*)</td>
<td>394.0</td>
<td>0.20</td>
<td>1.89</td>
<td>0.17</td>
<td>1.4</td>
</tr>
</tbody>
</table>

picture. It is clear that the observations of pulsars will continue to play an important part in testing general relativity and its alternatives. We expect to detect gravitational waves not only indirectly but also directly using pulsar observations (see corresponding contributions), and we have all reasons to believe that future searches will yield pulsars that can probe the space-time around black holes. Combined with the results of other experiments, namely the detection of gravitational waves with ground based detectors, we can expect a bright future for our understanding of gravity.

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Session 1

Pulsar Discovery I
The High Time Resolution Universe surveys for pulsars and fast transients

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Abstract. The High Time Resolution Universe survey for pulsars and transients is the first truly all-sky pulsar survey, taking place at the Parkes Radio Telescope in Australia and the Effelsberg Radio Telescope in Germany. Utilising multibeam receivers with custom built all-digital recorders the survey targets the fastest millisecond pulsars and radio transients on timescales of 64 s to a few seconds. The new multibeam digital filter-bank system at has a factor of eight improvement in frequency resolution over previous Parkes multibeam surveys, allowing us to probe further into the Galactic plane for short duration signals. The survey is split into low, mid and high Galactic latitude regions. The mid-latitude portion of the southern hemisphere survey is now completed, discovering 107 previously unknown pulsars, including 26 millisecond pulsars. To date, the total number of discoveries in the combined survey is 135 and 29 MSPs. These discoveries include the first magnetar to be discovered by its radio emission, unusual low-mass binaries, gamma-ray pulsars and pulsars suitable for pulsar timing array experiments.

Keywords. pulsars: general, surveys

1. Introduction
At the time of writing, the ATNF pulsar catalogue lists more than 2000 known pulsars (Manchester et al. 2005). The vast majority of these pulsars were discovered in large radio surveys, and more than half were discovered in surveys with the Parkes Radio Telescope. Much of this success is due to the low system temperature and large field of view provided by the 21-cm “Multibeam” receiver (Staveley-Smith et al. 1996). This receiver has 13 feeds, allowing us to survey 13 patches of sky at once, drastically reducing the time to survey a large area of sky. The Parkes Multi-beam Pulsar Survey (PMPS) (Manchester et al. 2001), Swinburne Intermediate Latitude Survey (Edwards et al. 2001) and its extensions (Jacoby et al. 2009) all used this receiver, in total discovering nearly 1000 pulsars. A 13-beam receiver also requires a ‘backend’ recorder capable of digitising 13 independent signals. For PMPS and associated surveys, an analogue filter-bank was developed capable of 96 3-MHz frequency channels per beam and recording each channel with 1-bit per 250\mu s sample. Although analogue systems are capable of finer frequency resolution, the complexity and large size of such instruments limited the number of channels.

The 13-beam analogue filter-bank is adequate for the detection of the majority of the pulsar population. However, for the distinct population of millisecond pulsars (MSPs), which typically have spin periods less than ~30 ms, dispersive delays in the interstellar medium can broaden the pulse significantly across the 3 MHz band. This reduces the sensitivity of the PMPS and similar surveys to MSPs with dispersion measures (DMs) greater than ~25 cm\(^{-3}\)pc (c.f. the mean DM of the known pulsar population is 230). Although harder to detect, MSPs are especially valuable objects. In the last decade,
Table 1. Comparison of the BPSR backend with the analogue filter-bank backend as used in the PMPS.

<table>
<thead>
<tr>
<th></th>
<th>PMPS</th>
<th>HTRU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (MHz)</td>
<td>340</td>
<td>288</td>
</tr>
<tr>
<td>Sample rate (µs)</td>
<td>64</td>
<td>250</td>
</tr>
<tr>
<td>Number of channels</td>
<td>870</td>
<td>96</td>
</tr>
<tr>
<td>Channel bandwidth (MHz)</td>
<td>0.39</td>
<td>3</td>
</tr>
<tr>
<td>Number of bits per sample</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Data rate (MB s⁻¹)</td>
<td>52</td>
<td>0.62</td>
</tr>
</tbody>
</table>

highlights of MSP science includes the pulsar with the fastest rotation period (in the globular cluster Terzan 5; Hessels et al. 2006), the double pulsar system (Burgay et al. 2003; Lyne et al. 2004) and its impressive tests of general relativity (Kramer et al. 2006), the ‘missing link’ between the low-mass X-ray binaries and the MSPs (Archibald et al. 2009), and detailed study of the interstellar plasma at au scales (You et al. 2007). Furthermore, timing of MSPs provides highly accurate parameters (Verbiest et al. 2009) possibly leading to the detection of gravitational waves in the near future (Hobbs et al. 2009).

In addition, 1-bit sampling and limited numbers of channels reduces the capacity to detect and characterise fast transients. Lorimer et al. (2007) reported the discovery of a burst of radio emission of unknown origin but seemingly at cosmological distance, which has sparked great debate over the origin of such events. Although this burst was of great significance, further study of these bursts would be aided by greater dynamic range and higher frequency and time resolution.

2. BPSR and the HTRU Survey

To improve upon the highly successful Parkes surveys with the 13-beam receiver, we conceived of the High Time Resolution Universe (HTRU) survey for pulsars and fast transients, with the aim of surveying the entire sky with increased sensitivity to MSPs and fast transient events. This has been made possibly by developing the Berkley-Parkes-Swinburne Recorder (BPSR), an all-digital multibeam pulsar backend. The digital spectrometers were originally based upon the the Internet Break-Out Board (IBOB) platform developed by the CASPER group at the University of California, Berkley, described in detail in McMahon (2008). In 2012, these were upgraded to use the Re-configurable Open Architecture Computing Hardware (ROACH) platform as part of an upgrade to the backend to support spectral line observations. The properties of BPSR (as used in the HTRU) and a comparison to those of the analogue system (as used in the PMPS) is given in Table 1. For further details on BPSR, see Keith et al. (2010). Figure 1 shows contours of constant pulse broadening time for the PMPS and the HTRU surveys, combining both scattering and dispersion broadening computed from the NE2001 model (Cordes & Lazio 2002). Clearly, BPSR provides much greater penetration into the Galactic plane than the filters used in the PMPS, limited only by scattering close to the Galactic Centre.

At Parkes, we are surveying the entire southern sky in three parts:

- **The Low-latitude** segment covers a thin strip of the Galactic plane, with latitude \(|b| < 3.5°\) and longitude \(-80° < l < 30°\). The 4300 s integration time is twice that of the PMPS, providing the most thorough survey of the inner Galactic plane to date. Here we primarily target faint pulsars deep in the Galactic plane.

- **The Mid-latitude** segment covers the majority of the Galaxy, limited by latitude
The HTRU surveys

Figure 1. Contours of constant pulse broadening timescale for lines of sight at \( b = 0 \) for a frequency of 1352 MHz. The values for the PMPS are shown in dashed lines and for the HTRU survey in solid lines, with contours at 0.5, 1, 5 and 10 ms. Scattering timescales and DMs were computed using the NE2001 model (Cordes & Lazio 2002). The Earth and the approximate location of the Galactic Centre (GC) are shown with crosses.

\(|b| < 15^\circ\) and longitude \(-120^\circ < l < 30^\circ\). The integration time is 540 s, which allows us to cover the large area of sky quickly. Here we focus on bright MSPs suitable for timing array projects.

- The **High-latitude** segment covers all sky south of declination \(+10^\circ\)\), integrating for 270 s per pointing. Here we primarily target bright MSPs and gather a snapshot of the transient sky at 64 \( \mu \)s resolution.

In addition, we are undertaking a complementary survey of the northern sky with the Effelsberg Radio Telescope at the same sensitivity, using a 7-beam multibeam receiver and digital backend system. More details on the northern HTRU survey can be found in Ng et al. (this proceedings) and references therein.

Observations of the southern HTRU survey started in 2007 and mid-latitude component of the survey is now complete, and observations have been made for \( \sim 80\% \) of the low-latitude and \( \sim 50\% \) of the high-latitude survey. Analysis of the survey has so far been limited to solitary pulsars, or those in orbits much longer than the observation time.

3. Overview of Discoveries

To date, the combined north and south HTRU surveys have discovered 135 pulsars, of which 29 are MSPs. Much of the survey is still being analysed, and so here we concentrate on the results of the mid-latitude portion of the southern survey, which accounts for 107 of the total discoveries and 26 MSPs. This compares favourably with the the predicted discovery rates from Keith et al. (2010), which indicates that the complete survey could discover as many as 800 previously unknown pulsars and more than 100 MSPs. Details of the first 12 MSP discoveries appear in Bates et al. (2011) and Keith et al. (2012), and the first 75 canonical pulsars in Bates et al. (2012). Several of these MSPs may be suitable for pulsar timing array experiments, with typical timing precision less than 1 \( \mu \)s. PSR J1017–7156 is especially notable in this regard with root-mean-square of the timing residuals being \( \sim 0.6 \mu \)s over two years, and this pulsar is already included in the Parkes...
Pulsar Timing Array. The rest of this section covers highlights of the HTRU discoveries to date.

3.1. First Magnetar Discovered by Radio

The first major result from the HTRU survey was not an MSP, but the discovery of PSR J1622–4950, a 4.3s pulsar with a very high inferred magnetic field strength, \( \sim 3 \times 10^{14} \text{G} \) (Levin et al. 2010). The pulsar exhibits large red noise in it’s timing residuals and has a highly variable pulse profile. In addition, the pulsar is clearly detectable up to 24GHz, exhibiting a similar profile morphology to that at lower frequencies (Keith et al. 2011). These characteristics lead us to conclude that this pulsar is a magnetar, the first to be discovered via its radio emission. Observations with the Australia Telescope Compact Array show possible evidence of a supernova remnant, and changes in the phase averaged flux density and polarisation (Levin et al. 2010; Anderson et al. 2012). Further observations at Parkes have demonstrated that although the typical pulse profile is \( \sim 2 \text{s} \) wide, individual profiles are composed of components with widths of \( \sim 20 \text{ms} \). The shape of the profile remains relatively constant with frequency, although the individual pulses narrow with frequency (Levin et al. 2012). Although the linear and circular polarisation changes in magnitude and by more than 50% from day-to-day, and the position angles swing can change wildly, we find that the linear polarisation is generally consistent with an aligned rotator (Levin et al. 2012).

3.2. Unusual Low-mass binaries

Binary pulsars with degenerate companions are broadly split into three groups: intermediate-mass binary pulsars, with heavy white dwarf or neutron star companions (IMBPs; \( M_c \sim 1 \text{M}_\odot \)); low-mass binary pulsars with light white dwarf companions (LMBPs; \( M_c \sim 0.2 \text{M}_\odot \)); and very low-mass binary pulsars that appear to have had a formation process that involves significant mass loss of the companion (VLMBPs; \( M_c \sim 0.02 \text{M}_\odot \)). Until recently, it had been thought that VLMBPs underwent a relatively long period of accretion, causing the pulsar to spin up to short spin periods (i.e. \(< 10 \text{ms}\)) and causing significant mass loss of the companion. However, the discovery of PSR J1502–6752, a 26.7ms pulsar in a 2.48 day orbit around a companion with minimum mass \( \text{0.02 M}_\odot \) (Keith et al. 2012) challenges that assumption. The true companion mass does, of course, depend on the inclination angle, and it is possible that we are observing these LMBPs close to face on. For the companion mass of PSR J1502–6752 to be greater than 0.1 \( \text{M}_\odot \), the inclination angle must be less than 13\(^\circ\), which has a probability of 0.025 of being drawn from a uniform distribution of three-dimensional orientations. It is also worth noting that, as mentioned by Freire et al. (2003), there is a distinct gap in the mass functions of the lowest mass binary MSPs between the VLMBPs. Therefore, if we disfavour the chance of a face-on system, then either the formation process of VLMBPs does not require a long accretion process, or that PSR J1502–6752 has an unlikely formation mechanism and so is inherently rare. We do not yet understand The formation mechanism of VLMBPs, and the discovery of PSR J1502–6752 undoubtedly complicates the picture further. The discovery of further VLMBPs would be greatly beneficial in determining if PSR J1502–6752 really is a unique, or if the spin period distribution of the VLMBPs is in fact wider than currently understood.

The HTRU survey has also uncovered a new class of binary pulsar, the ‘ultra low-mass binary pulsar’ having \( M_c \sim 0.001 \text{M}_\odot \), typified by PSR J1719–1438 (Bailes et al. 2011). These objects are discussed further in Ng et al. (this proceedings).
3.3. Polarisation of MSPs

The improvement in data recording systems and the greatly increasing number of known MSPs has means we now have a much better sample of high quality polarisation measurements of MSPs. From these observations we see that in many ways the polarisation of MSPs is very similar to the ‘normal’ pulsar population. In particular, there is a wide variety in the fraction of linear and circular polarisation and a non-negligible fraction are amenable to fitting using a geometric model of the emission, i.e. the rotating vector model (RVM; Radhakrishnan & Cooke 1969). However, many MSPs have very large pulse widths, especially when observed with high dynamic range (Yan et al. 2011), and in some cases the polarisation profiles can be very complex and do not obey the RVM (Ord et al. 2004). Keith et al. (2012) argue that this is evidence for a high emission height in MSPs (up to 50% of the light cylinder). This naturally leads to wide profiles, either because they are ‘aligned’ or have emission from both poles. In turn, this complicates the profile, making it hard to identify components in the profile and derive emission geometry. However, in general it seems that the polarised emission of MSPs is not more complex than in many slow pulsars. There has been success in untangling the complex position angle variations in slow pulsars through studies of polarised intensity on a pulse-by-pulse basis (e.g. Backer & Rankin 1980; Gil & Lyne 1995; Karastergiou et al. 2002). Future high-sensitivity observations may well be able to repeat this success in MSPs, giving us greater confidence in geometric interpretations of the RVM and a fuller picture MSP emission. High significance gamma-ray profiles of MSPs could also provide additional constraints on geometry, and test theories of radio emission from the outer magnetosphere.

3.4. RRATs and Transients

In addition to the MSP discoveries, we have also discovered 11 Rotating Radio Transients (RRATs; Burke-Spolaor et al. 2011b). We have detected many more transient events, with the majority most likely to be RRATs. We have also detected a number of so-called ‘pertyons’, bursts of terrestrial origin that exhibit frequency dependant delays similar to the $\nu^{-2}$ laws of dispersion in the interstellar plasma (Burke-Spolaor et al. 2011a). However, it is likely that if ‘extragalactic’ bursts such as the event of Lorimer et al. (2007) are detected in the HTRU surveys, the enhanced time and frequency resolution, in addition to the increased dynamic range, will allow for better characterisation of such bursts. We have also developed a real-time transient detection system, as part of the upgrade of the BPSR instrument. This provides important real-time monitoring of RFI, as well as the chance to follow up on significant radio transients within minutes of the burst arriving at the Earth.

4. The Future of the HTRU surveys

Although the mid-latitude survey is now complete, we are already re-processing this survey with greater sensitivity to relativistic binary pulsars. This has the potential to make important new discoveries, including systems more relativistic than the the double pulsar system PSR J0737–3039A/B. In addition, we have barely scratched the surface of the high and low-latitude parts of the southern hemisphere survey, nor much of the northern survey. The low-latitude survey is the deepest survey of the Galactic plane ever performed, and will make important constraints on the pulsar population, and on the timescales for RRATs and similar nulling pulsars (Burke-Spolaor et al. 2011b). Finally, the high-latitude survey covers a large area of sky that has never before been surveyed at this frequency, and the increased sensitivity to transient events makes will provide a powerful dataset for understanding and characterising short duration radio transients.
Acknowledgements

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The PALFA Survey: Going to great depths to find radio pulsars

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\textbf{Abstract.} The on-going PALFA survey is searching the Galactic plane ($|b| < 5\degree$, $32\degree < l < 77\degree$ and $168\degree < l < 214\degree$) for radio pulsars at 1.4 GHz using ALFA, the 7-beam receiver installed at the Arecibo Observatory. By the end of August 2012, the PALFA survey has discovered 100 pulsars, including 17 millisecond pulsars ($P < 30$ ms). Many of these discoveries are among the pulsars with the largest DM/P ratios, proving that the PALFA survey is capable of probing the Galactic plane for millisecond pulsars to a much greater depth than any previous survey. This is due to the survey’s high sensitivity, relatively high observing frequency, and its high time and frequency resolution. Recently the rate of discoveries has increased, due to a new more sensitive spectrometer, two updated complementary search pipelines, the development of online collaborative tools, and access to new computing resources. Looking forward, focus has shifted to the application of artificial intelligence systems to identify pulsar-like candidates, and the development of an improved full-resolution pipeline incorporating more sophisticated radio interference rejection. The new pipeline will be used in a complete second analysis of data already taken, and will be applied to future survey observations. An overview of recent developments, and highlights of exciting discoveries will be presented.

\textbf{Keywords.} Surveys, pulsars: general

1. Introduction

The PALFA survey is an on-going, large-scale, survey for radio pulsars tuned to find millisecond pulsars (MSPs). PALFA is similar to, but more sensitive than other on-going projects (e.g. HTRU-N/S, GBNCC, SPAN512, described by Ng et al., Keith et al., Lynch et al., and Desvignes et al., respectively, in these proceedings). MSPs are particularly useful for searches for the direct detection of nano-Hz gravitational waves using Pulsar Timing Arrays (e.g. van Haasteren et al. 2011), strong-field tests of relativistic theories of gravity (e.g. Kramer et al. 2006), studying the equation of state of ultra-dense matter (e.g. Demorest et al. 2010). Another main goal of the survey is to expand the known population of radio pulsars, to gain a better understanding of their overall numbers, the distribution of their properties, determine birth-rates, and estimate birth properties. The survey is sensitive to transient pulsars, such as nullers, rotating radio transients (RRATs), intermittent pulsars, and radio magnetars. Discoveries may also be young pulsars associated with high-energy emission, supernova remnants, or pulsar wind nebulae. PALFA has the potential for discovering even more exotic systems such as pulsar-black hole binaries, which could have profound ramifications for the understanding of gravitation (e.g. Wex and Kopeikin 1999).

The PALFA Survey makes use of the 7-beam L-band (1.4 GHz / 21-cm) receiver installed on the Arecibo Observatory’s William E. Gordon Telescope. Observing has focused on the plane of the Galaxy ($|b| < 5\degree$), in the two regions visible from Arecibo,
due to its transit design, the “inner Galaxy” (34° < l < 77°) and the “anti-centre” (168° < l < 214°) regions.

The Wideband Arecibo Pulsar Processor (WAPP) spectrometers used by the PALFA survey since its beginning in 2004 were replaced with the more sensitive Mock spectrometer system in 2009. The Mock set-up allows for ALFA’s full 320 MHz bandwidth to be recorded, more than tripling the bandwidth available compared to the older WAPP set-up. In 2009, before completely phasing out the WAPP spectrometers for use in the survey, both backends were run in parallel to ensure the quality of the data from the new system. The ALFA receiver’s system temperature is ~24 K, and the gain is ~10.4 K/Jy for the central beam and ~8.2 K/Jy for the outer beams (Cordes et al. 2006). The survey’s observing parameters, summarized in Table 1, are characterized by high time and frequency resolution. Integration times are 4.5 min for the inner Galactic region, and 2.25 min for the anti-centre region.

The high resolution employed by the PALFA survey allows for the dispersive smearing caused by free electrons in the interstellar medium along the line-of-sight to be almost completely removed for pulsars at any depth into the Galactic plane using incoherent dedispersion techniques. Scattering due to multi-path propagation still limits the depth to which the fastest spinning pulsars can be detected within the Arecibo-visible sky (see Figure 1, left).

The large collecting area and hence high gain of the Arecibo Observatory make the PALFA survey the most sensitive large-scale survey of the Galactic plane to date. The high sensitivity of the survey enables integration times far shorter than would be possible when using smaller telescopes, and reduces the total data volume of the survey. It is important to note that shorter observations are more computationally efficient to search, especially for pulsars in binary systems.

### 2. Processing

Processing of PALFA survey data is currently done with two complementary pipelines. One is based on the PRESTO suite of pulsar search code †. The other pipeline makes use of the BOINC-based‡ Einstein@Home distributed global volunteer computing platform¶.

Before data are distributed to processing sites the data are converted to 4-bits-per-sample PSRFITS format, and archived at Cornell University’s Center for Advanced Computing. All data are tracked by a database at Cornell. Data are automatically downloaded from the archive by processing sites.

† [http://www.cv.nrao.edu/~sransom/presto/](http://www.cv.nrao.edu/~sransom/presto/)
‡ [http://boinc.berkeley.edu/index.php](http://boinc.berkeley.edu/index.php)
2.1. PRESTO

The PRESTO pipeline first searches for, and removes, bright un-dispersed narrow-band impulsive, and periodic, radio frequency interference (RFI) signals in the data.

The pipeline then dedisperses the data with an assumed dispersion measure (DM) value, removing the corresponding frequency-dependent delay. Since the DM of unknown pulsars are not known a priori, 4188 (1140) dedispersed time series, each with a different trial DM value ranging from 0 to \( \sim 1000 \) pc cm\(^{-3}\), are generated when searching Mock (WAPP) observations. Each resulting time series is then searched in the time domain for bright individual pulses, and in the Fourier domain for periodic signals.

Each dedispersed time series is searched for single pulses. To increase sensitivity to pulses of width larger than the observation’s sampling time a series of boxcar matched filters of different widths are convolved with the data. A summary plot of all significant candidate pulses identified at all trial DMs is produced, and inspected.

In order to increase sensitivity to pulsars in binary systems a series of trial Fourier-domain templates, each corresponding to a constant acceleration, are used when searching the Fourier Transform of the dedispersed time series (see Ransom et al. 2002, for more details). Given the length of PALFA observations, and the number and range of trial acceleration values, the PRESTO pipeline maintains sensitivity to pulsars in binary orbits with periods as small as \( \sim 1 \) hour.

The PRESTO pipeline then identifies the most likely pulsar candidates from the list of periodicity signals identified. For each periodicity candidates the raw data are folded using its period and DM, and a diagnostic plot is produced. Also, a series of scoring heuristics are computed for each folded candidates. These are later used as input to Artificial Intelligence (AI) systems trained to identify pulsar-like candidates, and ignore RFI-like and noise-like signals that were folded by the pipeline. All periodic signals identified are summarized in overview diagnostic plots.

The PRESTO pipeline is run on computing resources at the University of British Columbia, and on the Guillimin supercomputer† managed by McGill University. Combined, 3000-6000 observations can be reduced per month, depending on contention for resources on Guillimin.

2.2. Einstein@Home

Prior to distributing data to volunteers’ computers, the Einstein@Home-based pipeline identifies, and masks narrow-band impulsive RFI in the time-domain. The pipeline also identifies periodic RFI, which is replaced by random noise. The pipeline then generates 3808 (628) dedispersed time series for Mock (WAPP) data, each with a different trial DM, up to \( \sim 1000 \) pc cm\(^{-3}\). These dedispersed time series that are transferred to volunteers’ computers to be analyzed.

Sensitivity to binary pulsars is improved by using 6662 circular orbital templates to demodulate the time series in the time domain. This technique is capable of detecting isolated pulsars (e.g. Knispel et al. 2010), and still maintains sensitivity to pulsars in binaries with orbital periods as short as \( \sim 11 \) min. The Fourier transform of each demodulated time series is searched for periodic signals. The top 100 signals are returned to the Einstein@Home servers where they are collated, diagnostics plots are created, and heuristic pulsar-identification algorithms are run.

No single pulse search is performed in the Einstein@Home analysis.

The Einstein@Home pipeline can make use of volunteers’ GPUs, if permitted. Processing on GPUs accounts for \( \sim 75\% \) of the pipeline’s processing power. The performance

† http://www.clumeq.ca/index.php/en/about/computers/guillimin
of the pipeline, and more importantly the GPU code, is constantly being improved, reducing the time required for analysis with each iteration. Currently, the Einstein@Home pipeline searches ~3000 observations per month.

2.3. Candidates

The PALFA collaboration uses a centralized database to store metadata and diagnostics for each observation, and details for candidates identified by processing. The database holds approximately six million candidates.

Candidates are primarily inspected using an online viewer available on the PALFA Survey’s portal on the CyberSKA website.† The viewer allows users to select candidates based on information in the database, including scoring heuristics, AI recommendations, and the usual observation/candidate information. The user interface provides one-click access diagnostic information and plots about the candidate being viewed, and the observation in which it was found. The candidate viewer also provides direct access to another web-application designed to track the most promising candidates, and their follow-up. Both applications, and others not mentioned here, are hosted at McGill University.

3. Results

By the end of August 2012, the PALFA survey has discovered 100 pulsars. The discovery rate increase significantly when the analysis of the Mock data began (see Figure 1, right). This is partly due to the increase of computing resources available. However, the number of discoveries per sq. deg. is higher for Mock data, owing to their higher sensitivity. The WAPP spectrometers have been used to discover 56 pulsars in 164 sq. deg. of PALFA data (1 pulsar per 2.9 sq. deg.) whereas 44 pulsars have been discovered in only 70 sq. deg. of Mock data (1 pulsar per 1.6 sq. deg.).

3.1. Highlights

The PALFA survey has made several exciting discoveries since its start, including:

† www.cyberska.org/palfa. Access is restricted to members of the PALFA Consortium.
PSR J1906+0746 \( (P=144 \text{ ms}; DM=212 \text{ pc cm}^{-3}) \) This binary pulsar has a characteristic age of \( \tau_c = \frac{P}{2P} = 112 \text{ kyr} \), making it the youngest known binary pulsar (Lorimer et al. 2006). Also, it is the second most relativistic binary pulsar system known. (See also, Kasian 2012).

PSR J1903+0327 \( (P=2.15 \text{ ms}; DM=298 \text{ pc cm}^{-3}) \) This Galactic MSP is in a binary orbit whose eccentricity of \( e = 0.44 \) challenges the standard MSP formation picture (Champion et al. 2008). Pulsar timing has measured the Shapiro delay, and the relativistic advance of periastron, allowing the determination of the pulsar’s mass (\( M_p = 1.67(2)M_\odot \)) and the companion’s mass (\( M_c = 1.029(8)M_\odot \)). Near-IR spectroscopic observations have identified the companion as a main-sequence star. Simulations suggest the current binary was formed from a triple-star system (Freire et al. 2011; Portegies Zwart et al. 2011).

PSR J1856+0245 \( (P=80.9 \text{ ms}; DM=650 \text{ pc cm}^{-3}) \) This young (\( \tau_c = 27 \text{ kyr} \)), highly energetic (\( \dot{E} = 4\pi^2 I PP^{-3} = 4.6 \times 10^{36} \text{ erg s}^{-1} \)) pulsar is coincident with the TeV \( \gamma \)-ray source HESS 1857+026, as well as a faint X-ray source AX J185651+0245 (Hessels et al. 2008; Rousseau et al. 2012).

PSR J1949+3106 \( (P=13.1 \text{ ms}; DM=164 \text{ pc cm}^{-3}) \) This binary MSP is in a circular (\( e = 4 \times 10^{-5} \)), whose inclination (\( i = 80^\circ \)) makes the detection of Shapiro delay possible in the timing data (Deneva et al. 2012). The measurement of Shapiro delay provides mass measurements of the pulsar (\( M_p = 1.47^{+0.31}_{-0.17} M_\odot \)) and of the companion (\( M_c = 0.85^{+0.14}_{-0.11} M_\odot \)). Detection of relativistic advance of periastron, which could be possible within a few years, will greatly reduce the uncertainties on the masses. Also, the absence of timing noise, the decent timing precision (\( \text{RMS}_{\text{TOA}} = 3.96 \mu s \)), and the as-of-yet unresolved pulse profile, coupled with Arecibo’s new PUPPI backend could make this pulsar useful for Pulsar Timing Array experiments.

3.1.1. Global distributed volunteer computing discoveries

The Einstein@Home platform’s first discovery was found in 2010 in a WAPP PALFA data (J2007+2722, Knispel et al. 2010). Since then, the Einstein@Home pipeline has discovered 22 additional pulsars, including four MSPs, and three binaries.

3.1.2. Distant MSPs

The PALFA survey has discovered 17 MSPs (defined here as \( P < 30 \text{ ms} \)). These pulsars are amongst the highest DM MSPs in the Galactic plane. The ratio DM/P can be used as a rough measure of the difficulty of finding a pulsar, since the smearing in time caused by DM is more detrimental to shorter period pulsars. The MSPs found in the PALFA survey make up a large proportion of the highest DM/P pulsars known (see Figure 2, left).

Also, by assuming the NE2001 model for the Galactic distribution of free-electron density (Cordes and Lazio 2002), it is possible to infer distances given the sky-position and DM of a pulsar. Figure 2 (right) shows the inferred positions of PALFA-discovered MSPs projected onto the plane of the Galaxy, compared to all other Galactic plane MSPs. The median distance to PALFA MSPs is 5.8 kpc, double that of other known Galactic MSPs (\( D_{\text{median}} = 2.9 \text{ kpc} \)), highlighting PALFA’s ability to find distant MSPs.

4. Future Outlook

The PALFA survey has observed only 10% of its nominal survey region with the Mock spectrometers, which are proving to be superior to the WAPPs due to their tripled bandwidth. The Mock spectrometers will be used as the survey continues, and will eventually be used to re-observe regions covered with the WAPPs.
Figure 2. Left: DM vs. Period for Galactic MSPs. Notice that red Xs, PALFA-discovered MSPs tend towards the top of the plot. These pulsars are generally thought to be harder to find. Right: A top-down view of the Galactic plane showing Galactic MSP. The PALFA-discovered MSPs (red Xs) are generally located deeper into the plane of the Galaxy. Distances are inferred from the DM using the NE2001 model.

In addition, an updated version of the PRESTO pipeline, including enhanced RFI mitigation, improved candidate optimization, additional diagnostic information, and a few bug fixes, is being beta-tested on the Guillimin supercomputer. The updated pipeline is already finding pulsars missed by the first analysis. Improved single pulse analyses based on the work of Spitler et al. (2012) are also being applied to the PALFA data taken thus far, and will be integrated into the survey’s standard data reduction, as will a modified version of the algorithm developed by Karako-Argaman et al. (in these proceedings).

With the 100 pulsars discovered to date, the improved data quality, additional computing resources available, and enhancement to the data reduction, the PALFA survey is well on its way to discovering hundreds of pulsars, including expanding the population of faint, distant MSPs it has already been successful at finding.

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The hunt for new pulsars with the Green Bank Telescope

Ryan S. Lynch, on behalf of the GBT 350 MHz Drift-scan survey and Green Bank North Celestial Cap survey collaborations

Abstract. The Green Bank Telescope (GBT) is the largest fully steerable radio telescope in the world and is one of our greatest tools for discovering and studying radio pulsars. Over the last decade, the GBT has successfully found over 100 new pulsars through large-area surveys. Here I discuss the two most recent—the GBT 350 MHz Drift-scan survey and the Green Bank North Celestial Cap survey. The primary science goal of both surveys is to find interesting individual pulsars, including young pulsars, rotating radio transients, exotic binary systems, and especially bright millisecond pulsars (MSPs) suitable for inclusion in Pulsar Timing Arrays, which are trying to directly detect gravitational waves. These two surveys have combined to discover 85 pulsars to date, among which are 14 MSPs and many unique and fascinating systems. I present highlights from these surveys and discuss future plans. I also discuss recent results from targeted GBT pulsar searches of globular clusters and Fermi sources.

Keywords. Pulsars: general, surveys

1. Introduction

Since their discovery 45 years ago, just over 2000 pulsars have been uncovered, enabling some of the most precise and fascinating astronomical discoveries over that same time span. The majority of these are radio pulsars that have been found in large-area surveys, though a significant fraction, especially of millisecond pulsars (MSPs), were found in targeted searches. Almost all surveys result in some new and often unexpected discovery, many of which have an impact beyond the study of neutron stars. Some highlights from only the past few years are: the double pulsar (Lyne et al. 2004), which has provided some of the best tests of strong-field general relativity (Kramer et al. 2006), as well pulsar-white dwarf systems that place stringent limits on tensor-vector-scalar theories of gravity (Bhat et al. 2008; Lazaridis et al. 2009; Freire et al. 2012); PSR J1614−2230, a 2 M⊙ MSP that has provided the best constraints yet on the equation of state of ultra-dense matter (Demorest et al. 2010); the unexpected discovery of a population of gamma-ray pulsars and MSPs (Abdo et al. 2009a; Abdo et al. 2009b); the discovery of rotating radio transients (RRATs) and the implication that they may outnumber traditional radio pulsars (McLaughlin et al. 2006); and three radio-emitting magnetars (Camilo et al. 2006; Camilo et al. 2007; Levin et al. 2010) that have shed light on the relationship between radio pulsars and magnetars. One of the most exciting prospects for the future is the direct detection of gravitational waves using a pulsar timing array (PTA) of ultra-high precision MSPs, which will help to usher in a new era of gravitational wave astronomy.
New pulsar surveys are important for continuing this tradition of discovery, especially in light of the need for more high-precision MSPs for use in PTAs. Different surveys often complement each other owing to different sky coverage and observing set-ups (e.g. high frequency surveys are more sensitive to distant pulsars with high dispersion measures (DMs), while low-frequency surveys are more sensitive to steep-spectrum pulsars). The National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia has a long history of discovering fascinating pulsars through large-area, low radio frequency surveys. The first of these low-frequency Green Bank pulsar surveys was carried out using the 92-m telescope by Damashek et al. (1978) at an observing frequency of 400 MHz and uncovered 17 pulsars. This was followed up by Dewey et al. (1985) and Stokes et al. (1985), also using the 92-m telescope at 390 MHz. The latter survey was sensitive to pulsars with periods $4 \leq P \leq 100$ ms but did not find any, leading the authors to conclude that the number of such pulsars must be small compared to long-period pulsars and providing early evidence that the then-newly discovered MSPs constituted a separate population with a distinct evolutionary history. Sayer et al. (1997) discovered a MSP (defined here as having $P < 20$ ms) and a $P = 40.9$ ms relativistic binary using the 43-m telescope at 370 MHz.

The Robert C. Byrd Green Bank Telescope (GBT) was built to replace the 92-m telescope and is the largest fully steerable telescope in the world. Over the past decade, the GBT has proven to be one of the best (and perhaps even the best) pulsar telescopes in the world, having discovered over 200 pulsars, many of which are MSPs. This is due to its excellent sensitivity and suite of low-noise receivers, its location in an environment with relatively little radio frequency interference (RFI), and state-of-the-art pulsar back-ends. The first low-frequency large-area survey carried out with the GBT was the 350 MHz North Galactic Plane survey (Hessels et al. 2008), which discovered 33 pulsars. The GBT has also revolutionized the field of globular cluster (GC) pulsars, uncovering 71 GC MSPs, more than any other telescope. It has also been instrumental in identifying radio counterparts to Fermi-selected pulsars and MSPs. Here, I will discuss the two most recent large-area GBT surveys, the GBT 350 MHz Drift-scan survey and the Green Bank North Celestial Cap (GBNCC) survey. I will also briefly discuss the GBT’s role in targeted searches of GCs and Fermi sources.

2. The 350 MHz Drift-scan Survey

The Drift-scan survey was completed between 2007 May and August while the GBT was closed for normal operations due to repair of the azimuth track. The main science motivation for the survey was the discovery of high-precision MSPs suitable for inclusion in the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), as well as other exotic pulsars. It covered a variety of right ascensions between declinations $-7.7^\circ \leq \delta \leq 38.4^\circ$ and $-20.7^\circ \leq \delta \leq 38.4^\circ$ (see Figure 2) using 50 MHz of bandwidth and 140-s long sections of data. In total, 10347 deg$^2$ were observed, totaling some 134 TB. Further details of the survey coverage, data processing, and sensitivity can be found in Boyles et al. 2012 and Lynch et al. 2012. Data processing for the Drift-scan survey is now complete, and 35 pulsars have been discovered, including 7 MSPs and recycled

† NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
†† I am grateful to Jason Boyles for compiling this list.
¶ http://nanograv.org
∥ 2800 deg$^2$ were reserved for the Pulsar Search Collaboratory (Rosen et al. 2010). See http://www.pulsarsearchcollaboratory.org/
pulsars. Twenty-four pulsars from early data processing are presented in Archibald et al. (2009), Boyles et al. 2012, and Lynch et al. 2012 along with complete timing solutions. An additional 11 pulsars have been discovered since this first round of detailed follow-up and are still being studied. Below I provide a few highlights.

- **PSR J0348+0432** is a 39-ms recycled pulsar in a short, 2.4-hr orbit around a white dwarf companion (Lynch et al. 2012). Optical imaging and spectroscopic follow-up of the companion have provided tight constraints on the mass of the white dwarf (Antoniadis et al., in prep), which is about 0.17 \( M_\odot \). The different binding energies of the pulsar and white dwarf are predicted by certain tensor-vector-scalar gravitational theories to lead to strong dipolar gravitational wave emission. Timing using the Arecibo telescope is already placing stringent limits on these theories in an as-yet unexplored strong-field regime (Antoniadis et al., in prep) and future timing will improve these constraints.

- **PSR J0337+1715** is a 2.7-ms MSP in a hierarchical triple, the first to be discovered in the field of the Galaxy. The inner companion appears to be a white dwarf with an outer companion of undetermined nature on a much longer orbit orbit. This system was only recently discovered during final processing of the Drift-scan data, but early timing is already showing evidence for secular changes to the orbital parameters of the inner binary due to three-body interactions (Ransom et al., in prep), making this system a precision dynamical laboratory.

- **PSR J2222−0137** is a 33-ms recycled pulsar with a minimum companion mass of 1.1 \( M_\odot \) (Boyles et al. 2012). The pulsar is nearby (\( D = 310 \) pc) and bright (\( S_{820 \text{ MHz}} \sim 2 \) mJy), and has been studied using the Very Long Baseline Array (Deller et al., in prep). The pulsar has also been the subject of a campaign to measure Shapiro delay (Boyles et al., in prep). These results will be presented in future publications.

- Two high-precision MSPs discovered in the Drift-scan survey have been released to NANOGrav and the International Pulsar Timing array.

- The well-known “missing link” MSP, **PSR J1023+0038** (Archibald et al. 2009) was one of the earliest Drift-scan discoveries and has shed light on the connection between low-mass X-ray binaries and MSPs.

- Thirty-three RRAT candidates have been discovered in the Drift-scan, with about six having already been confirmed. This marks a substantial increase in the size of the RRAT population (for details see the discussion by Karako-Argaman, these proceedings).

3. The Green Bank North Celestial Cap Survey

The GBNCC survey is the successor to the Drift-scan survey and was also carried out at 350 MHz, giving it excellent sensitivity to nearby, steep spectrum pulsars. It uses twice
Figure 2. Spin periods and DM-inferred distances of newly discovered GBNCC pulsars. The color bar indicates the distance above the Galactic plane. Nearly a dozen MSPs have DM-inferred distances ≤1 kpc, making them promising candidates for astrometric and multiwavelength study.

the bandwidth of the Drift-scan survey (100 MHz), 120-s pointed integrations, and the newer Green Bank Ultimate Pulsar Processor back-end (DuPlain et al. 2008), which provides increased dynamic range, bandwidth, and better resistance to RFI (though there is already little RFI). The science goals are the same, but with a particular emphasis on northern declinations, where there are fewer high-precision MSPs known, especially in the first stage of the survey. This is important for increasing the number of wide-separation baselines in PTAs and also probes a region of the Galaxy that has not been studied in as much detail as the Galactic plane. Stage I of the survey covered the north celestial cap (δ > 38°) and data taking was completed in 2011. We are currently conducting the second stage of the survey by moving towards lower declinations with the goal of eventually covering the entire sky visible to the GBT.

Data processing is being carried out at the Texas Advanced Computing Center† and especially using the Guillimin supercomputer operated by CLUMEQ‡. These substantial computing resources (up to 2048 CPUs are reserved for pulsar searching on Guillimin) have allowed us to reduce most of the data collected thus far, though we have only managed to do a preliminary analysis of the resulting pulsar candidates. These early results, however, are quite promising, with 50 new pulsars¶, including 9 new MSPs∥. Detailed follow-up of these new pulsars is ongoing, but I provide some early highlights below.

- **MSPs**: Three of the nine new MSPs appear to be excellent candidates for PTAs, and indeed, the 8.85-ms MSP PSR J0645+51 has already been released to NANOGrav and the IPTA. At least five MSPs are in binary systems. PSR J1816+4510 has a >0.16 M⊙ companion and has been detected with Fermi. There is also a UV/optical counterpart (Kaplan et al. 2012). PSR J0636+51 is a 2.9-ms MSP in a 1.5-hr orbit. The lower limit on the companion mass is a factor of two higher than that of the so-called “diamond

† http://www.tacc.utexas.edu/
‡ http://www.clumeq.ca/index.php/en/about/computers/guillimin
¶ Of the 50 new pulsars, 21 were identified by high school students through a summer internship program at McGill University, and 11 were identified by undergraduate students as part of the Advanced Arecibo Control Center program at the University of Texas at Brownsville and the University of Wisconsin-Milwaukee, demonstrating how education and outreach programs can be blended with real-world research.
∥ See http://arcc.phys.utb.edu/gbncc/ for an up-to-date list.
planet” (Bailes et al. 2011). PSR J1124+78 is a nearby \((D \sim 600 \text{ pc})\) binary MSP with a likely white dwarf companion, and we have proposed for time to look for an optical counterpart.

- **Intermediate Period Pulsars:** Five pulsars have periods \(20 \text{ ms} \leq P \leq 100 \text{ ms}\), and four have Galactic latitudes \(|b| > 10^\circ\). These are properties often seen in double-neutron star systems, and there is a possibility that at least one of these intermediate period pulsars is in a relativistic binary. The fifth has \(b \approx 1^\circ\), and its proximity to the plane raises the possibility that it is a young pulsar, though no supernova remnants have been found at the position of the pulsar in radio and X-ray catalogs. Further investigation is needed to determine the nature of these pulsars.

- **Nearby Pulsars:** Eleven pulsars (including five MSPs) have DM-inferred distances < 1 kpc (see Figure 3) according to the NE2001 free electron density model (Cordes & Lazio2002), and several of these have high 350 MHz flux densities. These are excellent candidates for obtaining parallax and proper motion measurements using very-long baseline interferometry, as well as for searching for counterparts at other wavelengths. One source in particular, PSR J0737+69, has a period of 6.8 s, making it the fifth slowest rotating radio pulsar known (though there are several magnetars and X-ray dim isolated neutron stars with similar or longer periods†). Its proximity makes it an excellent candidate for X-ray follow-up.

A more detailed analysis of pulsar candidates from the GBNCC survey, as well as ongoing data-taking and processing, will undoubtedly result in the discovery of many more pulsars in the near future.

4. Targeted Pulsar Searches with the GBT

The GBT has proven itself to be a superb instrument for finding pulsars through targeted searches, notably of GCs and unidentified Fermi sources. Since 2004, nearly all new GC pulsars have been found with the GBT. In fact, the GBT has discovered 71 GC pulsars, nearly half of the entire known population‡. The most promising GCs visible from the GBT have all been deeply searched (Ransom et al. 2004; Ransom et al. 2005; Freire et al. 2008; Lynch & Ransom 2011a; Lynch et al. 2011b; Lynch et al. 2012; Stairs et al., in prep), with highlights including 34 pulsars in Terzan 5 (Ransom et al. 2005), the fastest known rotator (Hessels et al. 2006) and potential super-massive neutron stars (Freire et al. 2008). Though the pace of discovery has slowed in recent years, GC pulsars are still being discovered with the GBT. For a more detailed discussion of GC pulsars, see the discussion by Paulo Freire in these proceedings.

Fermi has revolutionized the search for field radio pulsars, particularly MSPs. Radio emission from 45 MSPs and four long-period pulsars have been discovered by targeting bright, unidentified Fermi sources, and 26 of these have been found using the GBT (see Ray et al. (2012) for a complete list of Fermi MSPs and their discovery telescopes). See the discussions by Pablo Saz Parkinson and Lucas Guillemot in these proceedings for a more detailed discussion of Fermi pulsar searches.

5. Conclusions

Exciting and unique pulsars are still being discovered almost anywhere they are looked for, and the GBT continues to play an indispensable role in this. The Drift-scan and


‡ See http://www.naic.edu/~pfreire/GCpsr.html for an up-to-date list.
GBNCC surveys have combined to discover 85 pulsars, including 16 MSPs or recycled pulsars, in addition to 33 strong RRAT candidates. These include some truly fascinating sources that are enabling cutting-edge physics and astronomy. The continuation of GBNCC survey ensures that more discoveries are yet to come. Searches of GC are still sensitivity limited, and searches of unidentified Fermi sources continue with the promise of yet more MSPs. As such, the GBT should continue in its role as one of the best pulsar telescopes in the world.

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New results from LOFAR

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Abstract. The LOw Frequency Array, LOFAR, is a next generation radio telescope with its core in the Netherlands and elements distributed throughout Europe. It has exceptional collecting area and wide bandwidths at frequencies from 10 MHz up to 250 MHz. It is in exactly this frequency range where pulsars are brightest and also where they exhibit rapid changes in their emission profiles. Although LOFAR is still in the commissioning phase it is already collecting data of high quality. I will present highlights from our commissioning observations which will include: unique constraints on the site of pulsar emission, individual pulse studies, observations of millisecond pulsars, using pulsars to constrain the properties of the magneto-ionic medium and pilot pulsars surveys. I will also discuss future science projects and advances in the observing capabilities.

Keywords. pulsars: general, telescopes: LOFAR

1. Introduction

LOFAR is an interferometric array of dipole antenna stations distributed over the Netherlands and a few countries in Europe, that operates at the very low radio frequencies from 10 to 250 MHz. It consists of 24 core stations with the central part of about 300 m across occupied by 6 stations, which is called “Superterp”. The Superterp provides a collecting area comparable to that of the 100-m Green Bank Telescope with a beam size of \( \sim 0.5^\circ \) at 140 MHz. For the full core with a size of about 2 km across, it is already Arecibo-like collecting area and beam size of \( \sim 5^\circ \). At the moment there are also 9 remote stations and 8 international stations included in the array. The latter are twice as big as Dutch stations and they can operate independently from the rest of the array. They are very powerful telescopes in their own right, each with collecting area comparable to that of the 64-m Parkes radio telescope.

LOFAR’s frequency range spans from 10 to 250 MHz which is achieved by using two types of dipoles, low-band antennas (LBA) at 10–90 MHz and high-band antennas (HBA) at 110–250 MHz. The HBA dipoles have bow-tie shape and grouped into tiles of 16 dipoles each. There are 48 tiles in Dutch stations and 96 in the international stations. LOFAR operates at the lowest radio frequencies visible from the Earth as at 10 MHz there is a cut-off due to ionospheric reflection. Operating at these low frequencies, LOFAR covers the lowest 4 octaves of the radio window, that makes it a very unique telescope, the only one working at such low radio frequencies with huge instantaneous fractional bandwidth.
Figure 1. Hexagonal pattern of 127 tied-array beams formed around the pulsar B2217+47 using 12 HBA sub-stations of the Superterp. The beam with the pulsar is marked by the arrow. The cumulative signal-to-noise ratio is designated by the color scale. The white circle of about 5 degrees across represents the whole station beam of the single HBA sub-station.

2. LOFAR Capabilities

All of the beam-formed modes, capabilities and many commensal results are described in detail in our first LOFAR paper (Stappers et al. 2011). Here we highlight a few of those, focusing on new commissioning advancements.

Multiple station beams. LOFAR is a very flexible, electronically steered aperture array. It is possible to form multiple station beams on the sky and observe several pulsars simultaneously (Hessels et al. 2010; Stappers et al. 2011). This technology will be crucial for the SKA. By trading off bandwidth for beams, we can have as a standard up to 8 widely separated field-of-views (FOVs) and optionally up to 244.

Tied-array beams. Within each of the station beams we can also form multiple tied-array (TA) beams, applying proper phase delays between stations while adding them coherently. At the moment we can form TA beams only using 12 Superterp sub-stations, as they share the single clock. Figure 1 shows the hexagonal pattern of 127 TA beams formed around the pulsar B2217+47. The signal-to-noise ratio of the other TA beams is about one order of magnitude smaller than the beam at the location of the pulsar. With 127 tied-array beams we can cover the whole station beam which is shown by the white circle. The FOV of the station beam is large enough to cover the entire Andromeda galaxy and then we can map it with TA beams in one single observation. Moreover, we can form a few station beams to cover a larger FOV and customize individual narrow TA beams pointing at different targets. The highest number of TA beams formed in the commissioning observations so far was 217 (8 rings plus a central beam).

The list and description of all beam-formed modes that are well-tested and currently available to the wider community can be found on the LOFAR web-pages†. There are many possible modes or configurations, and the system is very flexible, to match different science goals. Different data products can be recorded, namely total intensity, full Stokes

† http://astron.nl/radio-observatory/observing-capabilities/depth-technical-information/major-observing-modes/beam-form
parameters, or complex voltage data. All data are written in HDF5‡ format and we are already working to read it directly with DSPSR¶ (van Straten & Bailes 2011) and PRESTO∥ (Ransom 2001) pulsar software.

RFI. The RFI environment is very clean, much better than anticipated. The reasons for this is that a) we are using 12-bit ADCs at the station level, so the dynamic range is high; and b) the dipoles are located very low to the ground and do not pick up a much terrestrial interference. Typically, we flag about 1–2% of data in HBA, and 3–4% in LBA range. Below 30 MHz, however, the data get very contaminated by RFI.

Full-core single-clock. We are currently working on expanding the number of stations that use the single clock, from six stations on the Superterp to the whole core of 24 stations within ~ 1 km radius. The work is ongoing and will be finished by the end of October 2012. This will further increase the raw sensitivity of the system by a factor 4!

3. LOFAR Highlights

Here I present some of our recent pulsar results; some are published or will be submitted soon.

Pulsar timing. LOFAR is very capable of, and we have already started doing, observations of millisecond pulsars (MSPs), as shown in Figure 2. LOFAR MSP profiles show a very high quality at such a low frequency in comparison with previously acquired data using the Puschino BSA phased-array at 103 MHz. These are the highest-quality detections of these pulsars ever made below 200 MHz. For the MSP J0034−0534 compar-

¶ http://dpsr.sourceforge.net
∥ http://www.cv.nrao.edu/~sransom/presto/
Ionospheric Faraday rotation calibration. We started Faraday rotation monitoring to be able to measure accurately pulsar rotation measures (RMs). Figure 3 (Sotomayor-Beltran et al. 2012) presents the observed Faraday depths for three pulsars together with the model predictions based on the total electron content (TEC) maps from the Royal Observatory of Belgium (ROB) and the International Geomagnetic Reference Field (IGRF11). It can be clearly seen that our measurements (circles) match the model (red triangles) very well. We are now getting down to very robust and precise RM measurements of about 0.1 rad m$^{-2}$. The observations presented used only 1/6 of the LOFAR’s available bandwidth, thus showing a great potential for even better RM measurements using the full bandwidth especially in the LBA band.

Dispersion measure vs. Profile variations. Hassall et al. (2012) studied dispersion measure (DM) and profile variations for four pulsars, B0329+54, B0809+74, B1133+16,
and B1919+21 using simultaneous wideband observations with the LOFAR LBA and HBA at 40–190 MHz, the Lovell telescope at 1.4 GHz, and Effelsberg radio telescope at 8 GHz. We found that the dispersion law is correct to better than 1 part in $10^5$ across our observing band. We also put unique constraints on emission heights for these pulsars using aberration/retardation arguments and show that, for instance, in the case of the pulsar B1133+16 all radio emission comes from a small region less than 59 km in altitude at a height of less than 110 km above the neutron star surface (only 0.2% of the light cylinder). We found no evidence for the super-dispersion delay previously reported at low frequencies (Shitov & Malofeev 1985; Kuzmin 1986) and suggest it could be caused by pulse profile evolution or a wrong fiducial point. We show that profile evolution has a significant impact on high-precision pulsar timing and should be taken into account.

**Low-frequency single-pulse studies.** Figure 4 (left) shows the remarkable profile evolution of the pulsar B0809+74 from 62 down to 15 MHz. We performed a thorough single-pulse analysis for the pulsars B0809+74 and B1133+16 that show quite interesting results. For more details about single-pulse studies of the pulsar B0809+74 see Kondratiev et al. (2012) in these proceedings.

**Pilot pulsar surveys.** We have already finished two pilot pulsar surveys with LOFAR. For more details about the survey setup, search pipelines and results, see Coenen et al. (2012) in these proceedings.

**Low-frequency pulsar profiles.** Some of the examples of LOFAR pulsar profiles at HBA and LBA bands were already shown in Stappers et al. (2011b). Currently we have already detected more than 110 pulsars in the HBA and 12 pulsars in the LBA. We expect these numbers to significantly increase in the very near future with the full-core single-clock, when the LOFAR raw sensitivity will be quadrupled. We are working on the
ultimate LOFAR pulsar profile paper, and in particular on profile alignment with the high-frequency WSRT and Jodrell Bank data.

Scattering studies. LOFAR’s low-frequency range and huge fractional bandwidth is ideal for pulsar scattering studies. Figure 4 (right) shows the benefits of the LOFAR’s huge fractional bandwidth where you can see a remarkable scattering tail from the pulsar B2111+46 changing across the band. This allows us to study precisely the frequency dependency of scattering parameters of this and other pulsars.

4. Future advancements

LOFAR commissioning work is continuing and there are significant improvements which are coming by the end of Fall 2012, namely:

- Expanding single clock to the full LOFAR core (end of October 2012). This will quadruple LOFAR’s raw sensitivity.
- Reading HDF5 data directly using DSPSR and PRESTO (nearly completed).
- Doubling (almost) of the available bandwidth to about 80 MHz by implementing the 8-bit mode and potentially even 4-bit (end of October 2012).
- Implementing online RFI excision (removal from raw data).
- Creating sub-arrays and true Fly’s Eye observations.

5. Conclusions

The results presented here have already proven the exceptional capabilities of the LOFAR and opened up the whole new window of comprehensive studies of pulsars at low frequencies. We have published first, intriguing results, with additional papers in preparation. The forthcoming implementation of the full-core single-clock, with the fourfold increase in sensitivity, will further enhance the LOFAR pulsar capabilities.

Acknowledgements

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Conducting the deepest all-sky pulsar survey ever: the all-sky High Time Resolution Universe survey

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Abstract. The extreme conditions found in and around pulsars make them fantastic natural laboratories, providing insights to a rich variety of fundamental physics and astronomy. To discover more pulsars we have begun the High Time Resolution Universe (HTRU) survey: a blind survey of the northern sky with the 100-m Effelsberg radio telescope in Germany and a twin survey of the southern sky with the 64-m Parkes radio telescope in Australia. The HTRU is an international collaboration with expertise shared among the MPIfR in Germany, ATNF/CASS and Swinburne University of Technology in Australia, University of Manchester in the UK and INAF in Italy. The HTRU survey uses multi-beam receivers and backends constructed with recent advancements in technology, providing unprecedentedly high time and frequency resolution, allowing us to probe deeper into the Galaxy than ever before. While a general overview of HTRU has been given by Keith at this conference, here we focus on three further aspects of HTRU discoveries and highlights. These include the ‘Diamond-planet pulsar’ binary J1719-1438 and a second similar system recently discovered. In addition, we provide specifications of the HTRU-North survey and an update of its status. In the last section we give an overview of the search for highly-accelerated binaries in the Galactic plane region. We discuss the computational challenges arising from the processing of the petabyte-sized HTRU survey data. We present an innovative segmented search technique which aims to increase our chances of discovering highly accelerated relativistic binary systems, potentially including pulsar-black-hole binaries.

Keywords. surveys, stars: neutron, pulsars: general, pulsars: individual: J1719-1438

1. ‘Planet-pulsar’ binaries

In 2009 HTRU discovered PSR J1719-1438, a 5.7-millisecond pulsar (MSP), with the Parkes 64-meter radio telescope. After follow-up timing it was shown that this pulsar is in a binary system with an orbital period of 2.2 hours. The mass of the companion has been found to be 0.00115\(M_\odot\), which is comparable to that of Jupiter (\(\sim 1.2 M_J\)). However with a minimum density of 23 g/cm\(^3\), this companion has physical properties which are clearly incompatible with those of Jupiter (\(\rho_J < 2\) g/cm\(^3\)). J1719-1438 does not show signs of solid-body eclipses, making it unlikely to be a black widow system (Fruchter, Stinebring & Taylor 1988).

Further optical observations with the Keck 10-m Telescope revealed that the companion is likely to be an ultralow-mass carbon white dwarf that has lost 99% of its mass, possibly the remains of the degenerate core of the original white dwarf. Ultracompact low-mass x-ray binaries are potential progenitors of this system, in which the companion has narrowly escaped complete destruction. In fact under such conditions carbon would be crystallised, hence the nickname ‘Diamond planet’ (Bailes et al. 2011).

A second such ‘planet-pulsar’ system has recently been discovered in the HTRU survey. This second system has parameters very similar to those of J1719-1438 (Table 1), with...
a companion mass of the order of magnitude of a planet. Further timing studies are currently underway to improve the phase-coherent timing solution (Thornton et al. in prep). These HTRU results may be shedding light on a previously unknown population of pulsars, and perhaps more of such systems will be discovered in the near future.

### Table 1. Comparison between the two 'Planet-pulsar' binaries.

<table>
<thead>
<tr>
<th></th>
<th>J1719-1438</th>
<th>Planet-pulsar n=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{spin}}$ (ms)</td>
<td>5.7</td>
<td>3.46</td>
</tr>
<tr>
<td>DM Distance (kpc)</td>
<td>1.2(3)</td>
<td>0.313</td>
</tr>
<tr>
<td>$P_{\text{orb}}$ (days)</td>
<td>0.09</td>
<td>0.32</td>
</tr>
<tr>
<td>$a \sin i$ (lt-s)</td>
<td>0.0018</td>
<td>0.002</td>
</tr>
<tr>
<td>$m_{\text{comp}}$ ($M_\odot$)</td>
<td>$\geq 0.00115$ ($\sim 1.2 , M_{\text{Jovian}}$)</td>
<td>$\geq 0.00076$ ($\sim 0.8 , M_{\text{Jovian}}$)</td>
</tr>
</tbody>
</table>

2. **HTRU-North survey with the Effelsberg Telescope**

The ongoing HTRU-North survey is being conducted using the 100-m Effelsberg radio telescope operated by the Max-Planck-Institut für Radioastronomie. HTRU-North is the first large-scale pulsar survey performed with the Effelsberg telescope. Most importantly, the survey includes the region north of $38^\circ$ Galactic latitude, which has remained unsurveyed for the last 20 years. As a twin to the HTRU-South survey, the integration lengths at Effelsberg have been scaled down to achieve the same sensitivity as that of the Parkes Telescope. See Table 2 for a summary of the specifications for both surveys.

### Table 2. Summary of the specifications of the HTRU-North and HTRU-South surveys.

<table>
<thead>
<tr>
<th></th>
<th>Northern survey</th>
<th>Southern survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>Effelsberg-100m</td>
<td>Parkes-64m</td>
</tr>
<tr>
<td>Sky coverage</td>
<td>$\delta &gt; -20^\circ$</td>
<td>$\delta &lt; +10^\circ$</td>
</tr>
<tr>
<td>$T_{\text{obs}}$ (s)</td>
<td>Low-lat: 1500</td>
<td>Low-lat: 4300</td>
</tr>
<tr>
<td></td>
<td>Mid-lat: 180</td>
<td>Mid-lat: 540</td>
</tr>
<tr>
<td></td>
<td>High-lat: 90</td>
<td>High-lat: 270</td>
</tr>
<tr>
<td>Receiver</td>
<td>7-beam 1.4-GHz receiver</td>
<td>13-beam 1.35-GHz receiver</td>
</tr>
<tr>
<td>Backend</td>
<td>Pulsar Fast Fourier Transform Spectrometer (PFFTS)</td>
<td>Berkeley-Parkes-Swinburne Recorder (BPSR)</td>
</tr>
<tr>
<td>$B$ (MHz)</td>
<td>300</td>
<td>340</td>
</tr>
<tr>
<td>$N_{\text{chans}}$</td>
<td>512</td>
<td>1024</td>
</tr>
<tr>
<td>$\Delta v_{\text{chan}}$ (MHz)</td>
<td>0.58</td>
<td>0.39</td>
</tr>
<tr>
<td>$T_{\text{temp}}$ (µs)</td>
<td>54</td>
<td>64</td>
</tr>
<tr>
<td>$N_{\text{pointings}}$</td>
<td>$\sim 180,000$</td>
<td>$\sim 43,000$</td>
</tr>
<tr>
<td>Total data (PB)</td>
<td>$\sim 5$</td>
<td>$\sim 1$</td>
</tr>
</tbody>
</table>

Observations of unidentified Fermi point sources were taken initially as a system test for the HTRU-North survey. This has led to the discovery of Effelsberg’s first ever MSP J1745+1017 (Barr et al. submitted). The HTRU-North survey officially began in 2010. Thus far, $\sim 10\%$ of the medium-latitude pointings have been processed. Already 12 pulsars have been discovered, highlights of which include J1946+3414, an MSP in a highly eccentric orbit, and young pulsar J2004+3427 with a characteristic age $<19$ kyr (Barr et al. in prep). Extrapolating from these statistics we expect to find $\sim 100$ new pulsars from the medium-latitude region alone. Population synthesis studies predict that of the order of 500 new pulsars are to be discovered from the complete HTRU-North survey, which includes $\sim 40$ new MSPs.
3. Searching for highly-accelerated binaries in the Galactic plane

Pulsars in tight binary orbits with other compact objects such as neutron stars and, potentially, black holes are of great interest as their strong gravitational fields provide the best tests for General Relativity (GR) and other theories of gravity. The best example of such a binary system so far is the Double Pulsar (Burgay et al. 2003, Lyne et al. 2004). The Double Pulsar has been used to obtain four independent tests of GR predictions and has shown that GR passes these yet most stringent tests with a measurement uncertainty of only 0.05% (Kramer et al. 2006). In fact, deliverable science scales directly with the compactness of the binary system to be discovered and our aim is the discovery and study of ultra-compact relativistic binary systems.

The deep Galactic-Plane survey is where the most relativistic binaries are expected to be found (Belczynski et al. 2002). In this region of sky within Galactic latitude $\pm 3.5^\circ$, we employ the longest integrations to maximise our sensitivity (see Table 2). However, the sheer volume of data poses great challenges in data manipulation and analysis. From the southern sky alone we expect to have about 250 TB of data. When it comes to searching for binary pulsars, the analysis procedure becomes very complicated, since the orbital parameters of the binary system must be taken into account, resulting in a large 7-dimensional parameter space. We have recently implemented an innovative pipeline targeting the search of binary systems. Our strategy is to approximate any unknown orbital motion as a simple line-of-sight acceleration. We split these long data sets into sections and search for binary systems using an acceleration range appropriate for the length of the section. We push the maximum achievable acceleration value to over 1200 m/s$^2$. In other words, within this acceleration range we can find a Double-Pulsar-like system deeper in the Galaxy with orbital periods shorter than 1 hour and would also be able to explore the parameter space occupied by expected pulsar-black-hole systems.

In order to probe the full parameter space for binary pulsars, we compute at least 1.46 million Fourier transform operations per data set. Such acceleration searches are obviously computationally very expensive and for example would have taken a single-CPU computer over 1400 years to completely process just the Southern Galactic Plane data. We are carrying out processing across multiple international high-performance computer clusters. As a system test we have first analysed the HTRU data set containing the Double Pulsar. We report a three-fold increase in sensitivity from the analysis with acceleration search compared to the analysis without (Figure 1), illustrating the importance of this binary search pipeline.

Figure 1. Observation time versus pulse phase plots for the Double Pulsar data set. (Left) Analysis without acceleration search on the full 72-min data results in a signal-to-noise ratio (SNR) of 11.73, only marginally above the detection limit. (Right) Analysis with acceleration search on a 9-min section results in an improved SNR of 31.79. The orbital motion of the Double Pulsar is clearly seen, as traced out by the blue line indicating the best fit model.
4. Conclusion

The HTRU-North survey with the Effelsberg Telescope began in 2010. Currently 20% of the medium-latitude and 5% of the high-latitude region have been observed, and ~10% of the medium-latitude data have been processed. This has led to the discovery of 13 new pulsars, including one MSP and one Fermi MSP (Figure 2). For the HTRU-South survey, observations of the medium-latitude region have been completed. 40% of the high-latitude and more than 80% of the low-latitude region have been observed. Over 120 new pulsars have been found in the HTRU-South survey, including 27 MSPs (Figure 2). Highlight discoveries are for example the magnetar PSR J1622-4950 (Levin et al. 2010), ‘planet-pulsar’ binaries as mentioned in §1 and transient objects (Burke-Spolaor et al. 2011). The HTRU low-latitude data will provide the deepest large-scale search thus far in the Galactic plane region. Up to now we have processed, without acceleration searches, 15% of the Galactic Plane data from the southern sky. Already we have discovered 23 new pulsars and redetected about 200 known pulsars. An innovative ‘acceleration search’ pipeline has been implemented recently, targeting the search for binary systems in the low-latitude data. This processing will surely return even more exciting new discoveries.

Figure 2. Up-to-date HTRU discoveries overplotted on the Haslam et al. (1982) sky map. Circles indicate new HTRU-South pulsars (red: normal pulsars, black: MSPs). Squares indicate new HTRU-North pulsars (yellow: normal pulsars, black: MSPs). Orange stars indicate previously known pulsars.

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A search for pulsars in the central parsecs of the Galactic center

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\textbf{Abstract.} The discovery of a pulsar or pulsars orbiting near the Galactic Center (GC) could offer an unprecedented probe of strong-field gravity, the properties of our galaxy’s supermassive black hole and insights into the paradoxical star formation history of the region. However, searching for pulsars near the GC is severely hampered by the large electron densities along our line of sight and the scattering-induced pulse broadening of the pulsar emission observed through it. As the broadened pulse length approaches the pulsar period, the periodicity in pulsar emission becomes nearly undetectable. Searches extended to higher frequencies, in an effort to reduce scattering, suffer from reduced intrinsic flux, higher system temperatures and increased atmospheric opacity. We are currently attempting to mitigate the challenges associated with searching for pulsars near the GC by employing new wide bandwidth receivers, upgraded IF distribution systems and novel digital spectrometers in a GC pulsar search campaign at the Green Bank Telescope in West Virginia, USA.

Our search will cover two frequency bands, from 12-15 GHz (Ku Band) and 18-26 GHz (K Band), during a total of approximately 30 hours of observations, with expected characteristic 10-sigma sensitivities between 5-10 micro-Jy. Our first observations are scheduled for mid-March 2012. Here we will present the status of our observations and initial results.
Session 2

Pulsar Genesis

Neutron-star formation and birth properties
Structure of Quark Stars

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Abstract. This paper gives an brief overview of the structure of hypothetical strange quarks stars (quark stars, for short), which are made of absolutely stable 3-flavor strange quark matter. Such objects can be either bare or enveloped in thin nuclear crusts, which consist of heavy ions immersed in an electron gas. In contrast to neutron stars, the structure of quark stars is determined by two (rather than one) parameters, the central star density and the density at the base of the crust. If bare, quark stars possess ultra-high electric fields on the order of \(10^{18}\) to \(10^{19}\) V/cm. These features render the properties of quark stars more multifaceted than those of neutron stars and may allow one to observationally distinguish quark stars from neutron stars.

Keywords. neutron stars, quark stars, pulsars, strange quark matter, equation of state

\section{Introduction}

The theoretical possibility that quark matter made of up, down and strange quarks (so-called strange quark matter; Farhi & Jaffe 1984) may be more stable than ordinary nuclear matter has been pointed out by Bodmer (1971), Terazawa (1979), and Witten (1984). This so-called strange matter hypothesis constitutes one of the most startling possibilities regarding the behavior of superdense matter, which, if true, would have implications of fundamental importance for cosmology, the early universe, its evolution to the present day, and astrophysical compact objects such as neutron stars and white dwarfs (see Alcock & Farhi 1986, Alcock & Olinto 1988, Aarhus 1991, Weber 1999, Madsen 1999, Glendenning 2000, Weber 2005, Page & Reddy 2006, Sagert et al. 2006, and references therein). The properties of quark stars are compared with those of neutron stars in Table 1 and Fig. 1. Even to the present day there is no sound scientific basis on which one can either confirm or reject the hypothesis so that it is a serious possibility of fundamental significance for various (astro) physical phenomena.

The multifaceted properties of these objects are reviewed in this paper. Particular emphasis is is put on stellar properties such as rapid rotation, ultra-high electric surface fields, and rotational vortex expulsion, which may allow one to observationally discriminate between quark stars and neutron stars and–ultimately–prove or disprove the strange quark matter hypothesis. Further information on the existence of quark stars may come
Table 1. Theoretical properties of quark stars and neutron stars compared.

<table>
<thead>
<tr>
<th>Quark Stars</th>
<th>Neutron Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Made entirely of deconfined up, down, strange quarks, and electrons</td>
<td>Nucleons, hyperons, boson condensates, deconfined quarks, electrons, and muons</td>
</tr>
<tr>
<td>Quarks ought to be color superconducting</td>
<td>Superfluid neutrons</td>
</tr>
<tr>
<td>Energy per baryon $\lesssim 930$ $\text{MeV}$</td>
<td>Energy per baryon $&gt; 930$ $\text{MeV}$</td>
</tr>
<tr>
<td>Self-bound ($M \propto R^3$)</td>
<td>Bound by gravity</td>
</tr>
<tr>
<td>Maximum mass $\sim 2M_\odot$</td>
<td>Same</td>
</tr>
<tr>
<td>No minimum mass</td>
<td>$\sim 0.1M_\odot$</td>
</tr>
<tr>
<td>Radii $R \lesssim 10 - 12$ km</td>
<td>$R \gtrsim 10 - 12$ km</td>
</tr>
<tr>
<td>Baryon number $B \lesssim 10^{57}$</td>
<td>$10^{56} \lesssim B \lesssim 10^{57}$</td>
</tr>
<tr>
<td>Electric surface fields $\sim 10^{18}$ to $\sim 10^{19}$ V/cm</td>
<td>Absent</td>
</tr>
<tr>
<td>Can be bare (pure quark stars) or enveloped in thin nuclear crusts (mass $10^{-5}M_\odot$)</td>
<td>Not possible</td>
</tr>
<tr>
<td>Density of crust is less than neutron drip i.e., posses only outer crusts</td>
<td>Density of crust above neutron drip i.e., posses inner and outer crusts</td>
</tr>
<tr>
<td>Form two-parameter stellar sequences</td>
<td>Form one-parameter stellar sequences</td>
</tr>
</tbody>
</table>

from quark novae, hypothetical types of supernovae which could occur if neutron stars spontaneously collapse to quark stars (Ouyed et al. 2002).

2. Quark-Lepton Composition of Quark Stars

Quark star matter is composed of the three lightest quark flavor states (up, down, and strange quarks). Per hypothesis, the energy per baryon of such matter is lower than the energy per baryon of the most stable atomic nucleus, $^{56}\text{Fe}$. Since stars in their lowest energy state are electrically charge neutral to very high precision, any net positive quark charge must be balanced by electrons. The concentration of electrons is largest at low densities due to the finite strange-quark mass, which leads to a deficit of net negative quark charge. If quark star matter forms a color superconductor (Rajagopal & Wilczek 2001, Alford 2001, Alford et al. 2008, and references therein) in the Color-Flavor-Locked (CFL) phase the interiors of quarks stars will be rigorously electrically neutral with no need for electrons, as shown by Rajagopal & Wilczek (2001). For sufficiently large strange quark masses, however, the low density regime of quark star matter is rather expected to form other condensation patterns (e.g. 2SC, CFL-$K^0$, CFL-$K^+$, CFL-$\pi^0$, ...) in which electrons will be present (Rajagopal & Wilczek 2001, Alford 2001, Alford et al. 2008). The presence of electrons in quark star matter is crucial for the possible existence of a nuclear crust on quark stars. As shown by Alcock et al. (1986), Kettner et al. (1995), and Alcock & Olinto (1988), the electrons, because they are bound to strange matter by the Coulomb force rather than the strong force, extend several hundred fermi beyond the surface of the strange star. Associated with this electron displacement is a electric dipole layer which can support, out of contact with the surface of the strange star, a crust of nuclear material, which it polarizes (Alcock et al. 1986, Alcock & Olinto 1988). The maximum possible density at the base of the crust (inner crust density) is determined by neutron drip, which occurs at about $4.3 \times 10^{11}$ $\text{g/cm}^3$.

3. Bare versus Dressed Quark Stars and Eddington Limit

A bare quark star differs qualitatively from a neutron star which has a density at the surface of about 0.1 to 1 $\text{g/cm}^3$. The thickness of the quark surface is just $\sim 1$ fm, the
length scale of the strong interaction. The electrons at the surface of a quark star are held to quark matter electrostatically, and the thickness of the electron surface is several hundred fermis. Since neither component, electrons and quark matter, is held in place gravitationally, the Eddington limit to the luminosity that a static surface may emit does not apply, so that bare quark stars may have photon luminosities much greater than $10^{38}$ erg/s. It was shown by Usov (1998) that this value may be exceeded by many orders of magnitude by the luminosity of $e^+e^-$ pairs produced by the Coulomb barrier at the surface of a hot strange star. For a surface temperature of $\sim 10^{11}$ K, the luminosity in the outflowing pair plasma was calculated to be as high as $\sim 3 \times 10^{51}$ erg/s. Such an effect may be a good observational signature of bare strange stars (Usov 2001a, Usov 2001b, Usov 1998, and Cheng & Harko 2003). If the strange star is enveloped in a nuclear crust, however, which is gravitationally bound to the strange star, the surface, made of ordinary atomic matter, would be subject to the Eddington limit. Hence the photon emissivity of such a “dressed” quark star would be the same as for an ordinary neutron star. If quark matter at the stellar surface is in the CFL phase the process of $e^+e^-$ pair creation at the stellar quark matter surface may be turned off. This may be different for the early stages of a very hot CFL quark star (Vogt et al. 2004).

4. Mass-Radius Relationship of Quark Stars

The mass-radius relationship of bare quark stars is shown in Fig. 2. In contrast to neutron stars, the radii of self-bound quark stars decrease the lighter the stars, according to $M \propto R^3$. The existence of nuclear crusts on quark stars changes the situation drastically (Glendenning et al. 1995, Weber 1999, and Weber 2005). Since the crust is bound gravitationally, the mass-radius relationship of quark stars with crusts is then qualitatively similar to neutron stars.

In general, quark stars with or without nuclear crusts possess smaller radii than neutron stars. This feature implies that quark stars posses smaller mass shedding periods than neutron stars. Due to the smaller radii of quarks stars, the complete sequence of such objects—and not just those close to the mass peak, as it is the case for neutron stars—can sustain extremely rapid rotation (Glendenning et al. 1995, Weber 1999, and Weber 2005). In particular, a strange star with a typical pulsar mass of around $1.45 M_\odot$ can rotate at Kepler (mass shedding) periods as small as $0.55 \lesssim P_K/\text{msec} \lesssim 0.8$ (Glendenning & Weber).
1992, and Glendenning et al. 1995). This range is to be compared with $P_K \sim 1$ msec obtained for neutron stars of the same mass (Weber 1999).

Another novelty of the strange quark matter hypothesis concerns the existence of a new class of white-dwarf-like objects, referred to as strange (quark matter) dwarfs (Glendenning et al. 1995). The mass-radius relationship of the latter may differs somewhat from the mass-radius relationship of ordinary white-dwarf, which may be testable in the future. Until recently, only rather vague tests of the theoretical mass-radius relation of white dwarfs were possible. This has changed dramatically because of the availability of new data emerging from the Hipparcos project (Provençal 1998). These data allow the first accurate measurements of white dwarf distances and, as a result, establishing the mass-radius relation of such objects empirically.

### 5. Pulsar Glitches

Of considerable relevance for the viability of the strange matter hypothesis is the question of whether strange stars can exhibit glitches in rotation frequency. From the study performed by Glendenning & Weber (1992) and Zdunik et al. (2001) it is known that the ratio of the crustal moment of inertia to the total moment of inertia varies between $10^{-3}$ and $\sim 10^{-5}$. If the angular momentum of the pulsar is conserved in a stellar quake one obtains for the change of the star's frequency $\Delta \Omega/\Omega \sim (10^{-5} - 10^{-3})f$, where $0 < f < 1$ (Glendenning & Weber 1992). The factor $f$ represents the fraction of the crustal moment of inertia that is altered in the quake. Since the observed glitches have relative frequency changes $\Delta \Omega/\Omega = (10^{-9} - 10^{-6})$, a change in the crustal moment of inertia of $f \leq 0.1$ would cause a giant glitch (Glendenning & Weber 1992). Moreover it turns out that the observed range of the fractional change in the spin-down rate, $\dot{\Omega}$, is consistent with the crust having a small moment of inertia and the quake involving only a small fraction $f$ of that. For this purpose we write $\Delta \Omega/\Omega > (10^{-1} \text{ to } 10) f$ (Glendenning & Weber 1992). This relation yields a small $f$ value, i.e., $f < (10^{-4} \text{ to } 10^{-1})$, in agreement with $f \leq 0.1$ established just above. For these estimates, the measured values of $(\Delta \Omega/\Omega)/(\Delta \Omega/\dot{\Omega}) \sim 10^{-6}$ to $10^{-4}$ for Crab and Vela, respectively, have been used.
6. Possible Connection to CCOs

One of the most amazing features of quark stars concerns the possible existence of ultra-high electric fields on their surfaces, which, for ordinary quark matter, is around $10^{18}$ V/cm. If strange matter forms a color superconductor, as expected for such matter, the strength of the electric field may increase to values that exceed $10^{19}$ V/cm. The energy density associated with such huge electric fields is on the same order of magnitude as the energy density of strange matter itself, which alters the masses and radii of strange quark stars at the 15% and 5% level, respectively (Negreiros et al. 2009). Such mass increases facilitate the interpretation of massive compact stars, with masses of around $2 M_\odot$, as strange quark stars (see also Rodrigues et al. 2011).

The electrons at the surface of a quark star are not necessarily in a fixed position but may rotate with respect to the quark matter star (Negreiros et al. 2010). In this event magnetic fields can be generated which, for moderate effective rotational frequencies between the electron layer and the stellar body, agree with the magnetic fields inferred for several Compact Central Objects (CCOs). These objects could thus be interpreted as quark stars whose electron atmospheres rotate at frequencies that are moderately different ($\sim 10$ Hz) from the rotational frequency of the quark star itself.

Last but not least, we mention that the electron surface layer may be strongly affected by the magnetic field of a quark star in such a way that the electron layer performs vortex hydrodynamical oscillations (Xu et al. 2012). The frequency spectrum of these oscillations has been derived in analytic form by Xu et al. (2012). If the thermal X-ray spectra of quark stars are modulated by vortex hydrodynamical oscillations, the thermal spectra of compact stars, foremost central compact objects (CCOs) and X-ray dim isolated neutron stars (XDINs), could be used to verify the existence of these vibrational modes observationally. The central compact object 1E 1207.4-5209 appears particularly interesting in this context, since its absorption features at 0.7 keV and 1.4 keV can be comfortably explained in the framework of the hydro-cyclotron oscillation model (Xu et al. 2012).

A study which looks at the thermal evolution of CCOs is presently being carried out by Yang et al. (2012). Preliminary results indicate that the observed temperatures of CCOs can be well reproduced if one assumes that these objects are small quark matter objects with radii less than around 3 km.

7. Possible Connection to SGRs, AXPs, and XDINs

If quarks stars are made of color superconducting quark matter rather than normal non-superconducting quark matter. If rotating, superconducting quark stars ought to be threaded with rotational vortex lines, within which the star’s interior magnetic field is at least partially confined. The vortices (and thus magnetic flux) would be expelled from the star during stellar spin-down, leading to magnetic reconnection at the surface of the star and the prolific production of thermal energy. Niebergal et al. (2010) have shown that this energy release can re-heat quark stars to exceptionally high temperatures, such as observed for Soft Gamma Repeaters (SGRs), Anomalous X-Ray pulsars (AXPs), and X-ray dim isolated neutron stars (XDINs). Moreover, numerical investigations of the temperature evolution, spin-down rate, and magnetic field behavior of such superconducting quark stars suggest that SGRs, AXPs, and XDINs may be linked ancestrally (Niebergal et al 2010).

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Numerical modeling of core-collapse supernovae and compact objects

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Abstract. Massive stars ($M \geq 10M_\odot$) end their lives with spectacular explosions due to gravitational collapse. The collapse turns the stars into compact objects such as neutron stars and black holes with the ejection of cosmic rays and heavy elements. Despite the importance of these astrophysical events, the mechanism of supernova explosions has been an unsolved issue in astrophysics. This is because clarification of the supernova dynamics requires the full knowledge of nuclear and neutrino physics at extreme conditions, and large-scale numerical simulations of neutrino radiation hydrodynamics in multi-dimensions. This article is a brief overview of the understanding (with difficulty) of the supernova mechanism through the recent advance of numerical modeling at supercomputing facilities. Numerical studies with the progress of nuclear physics are applied to follow the evolution of compact objects with neutrino emissions in order to reveal the birth of pulsars/black holes from the massive stars.

Keywords. stars: massive, stars: pulsars, stars: neutron, supernovae: general, methods: numerical, neutrinos, equation of state

1. Introduction

Supernova explosions are fascinating phenomena in the Universe (Bethe 1990). First of all, they have bright displays by gigantic explosions, some of which were recorded even in the old Chinese literature, as in the case of SN 1054 (the Crab nebula). They are named as guest stars, which is the same expression for the description of SN 1054 noted in the old Japanese literature. Secondly, they are associated with bursts of neutrinos, as in the case of SN 1987A (Hirata et al. 1987). In this event, neutrinos from the supernova were detected at terrestrial detectors. They revealed the importance of neutrinos in the supernova mechanism. This detection also led to the Nobel Prize in Physics in 2002 (Koshiba 1992, 2003). Most importantly, the supernova is the birthplace of compact objects: neutron stars and black holes. It is essential to understand the supernova mechanism to know the distribution of compact objects from massive stars, together with the information on mass and rotation.

Numerical modeling of core-collapse supernovae is the heart of the problem in order to grasp the timeline from massive stars to pulsars. Massive stars of $\sim 20M_\odot$ evolve for $\sim 10^7$ years with the formation of Fe core at the end of life. Gravitational collapse of the Fe core leads to core bounce, launch of shock wave and a resulting explosion in $\sim 1$ s. At center, a proto-neutron star is born and evolves thermally by emitting supernova neutrinos for $\sim 20$ s (e.g. Pons et al. 1999). It further cools down by radiation for $\sim 10^2$-$10^5$ years as a cold neutron star (e.g. Page et al. 2004). What one wants to know is the connection between the stellar evolution and the neutron star modeling. To bridge a gap between massive stars and pulsars, one needs to perform the supernova simulations, which are the most difficult part of the problem. This article describes ongoing challenges to clarify the
supernova explosions with multi-physics at extreme conditions in 3 dimensions toward
the goal to reveal the birthplace of neutron stars.

2. Challenges to understand the supernova mechanism

Despite the longstanding efforts over four decades, it is still not a simple task to re-
produce supernova explosions in numerical modeling (Janka 2012, Kotake et al. 2012a).
Among many issues of the supernova modeling, three major aspects of the challenges
are: exotic conditions, counteracting ∼1% effects and multi-dimensions. To tackle these
difficult problems, it is necessary to perform large-scale simulations on the latest super-
computers.

To explain the current challenges in supernova physics, let us look into the details of
supernova mechanism. Starting from the Fe core of the massive star, the gravitational
collapse begins due to electron captures and photo-dissociations. The former reactions
produce neutrinos, which escape freely at the beginning. These neutrinos are trapped
inside the core at high densities during the collapse. Further collapse leads to the core
bounce at just above the nuclear matter density, where the nuclear repulsive force is
dominant. The shock wave is launched at the core bounce due to the stiffness of dense
matter. If the shock wave propagates outwardly and reach the surface of the Fe core, this
is the supernova explosion, which leaves the proto-neutron star and emits the supernova
neutrinos. The proto-neutron star settles down as a cold neutron star afterward. The
most difficult part among these stages is the way from the core bounce to the explosion
with the three major challenges in the following subsections.

2.1. Nuclear physics at extreme conditions

One of the key ingredients in the supernova modeling is nuclear physics at extreme
conditions. It is mandatory to provide the properties of hot-dense matter (the equation of
state) and the rates of neutrino reactions in the supernova core for numerical simulations.
The density inside the supernova core becomes very high, being dense more than that in
nuclei. The matter becomes very neutron-rich as compared with the stable nuclei such
as \(^{56}\text{Fe}\). The temperature may rise beyond \(\sim 10^{12}\) K (\(\sim 10\) MeV) in the central core,
which is different from the cold neutron star case. In addition, it is necessary to consider
the neutrino reactions under the influence of the hot-dense matter. One needs energy-
and angle-dependent neutrino reaction rates for emission, absorption, scattering and pair
processes. Neutrino processes via all targets including nucleons, nuclei and leptons must
be considered (e.g. Burrows et al. 2006).

As for the equation of state (EOS), it is a challenging task to provide the data set
of EOS for wide range of density, temperature and composition for the supernova sim-
ulations. Although there are many results of the EOS for cold neutron stars, the set of
EOS for supernovae have been limited before (Lattimer & Swesty 1991). There are con-
tinuous efforts to provide nuclear data for supernovae with the advance of experimental
and theoretical nuclear physics since the 1990s. Experimental data of unstable nuclei
became available at radioactive nuclear beam facilities along with the advance of nuclear
many body theories (Serot & Walecka 1986, Brockmann & Machleidt 1990). Systematic
measurements of the radii of neutron rich isotopes are valuable inputs to constrain the
interaction in the nuclear models for supernova EOS (Shen et al. 1998a, 1998b, 2011).

The two EOS tables by Lattime-Swesty and Shen et al. have been popular in many
supernova simulation studies. There is recent progress of the EOS tables at low and
high densities. One direction is extension to include exotic degrees of freedom such as
hyperons and quarks at high densities (Ishizuka et al. 2008, Sagert et al. 2009, Nakazato
et al. 2010a). The other direction is extension to consider the mixture of nuclei at low densities (Hempel et al. 2012). Recent observations of neutron star masses and radii are valuable to constrain the behavior of EOS at high densities. The observation of the massive neutron star of $\sim 2M_\odot$ (Demorest et al. 2010) is strong constraint to select the EOS sets for supernova simulations. Determination of the neutron star radii is also influential (Steiner et al. 2010) and needs further careful analysis with model dependence (Suleimanov et al. 2011).

2.2. Neutrinos in supernova dynamics
An important key for the successful explosion is the counteracting 1% effects. Neutrinos are playing a critical role to determine the energy budget in the supernova dynamics. Since the Fe core of $\sim 10^3$ km collapses to the neutron star of $\sim 10$ km, there is gravitational energy release, which amounts to $\sim 10^{53}$ erg. The explosion energy including kinetic, internal and potential energies is $\sim 10^{53}$ erg from observations. Although the explosion energy sounds just like a fraction of the gravitational energy release, the most of the energy are actually carried away as supernova neutrinos. The total energy of the emitted neutrinos amounts to $\sim 10^{53}$ erg from the observation of the supernova neutrinos. Therefore, only 1% is used for the explosion out of the total release of the emitted neutrinos. To understand this delicate role of neutrinos, careful evaluation of the neutrino-matter interaction is essential in every stage of the supernova dynamics.

It is helpful to describe further some of the important stages as examples of the 1% effects or the issue of $10^{51}$ erg. At the early stage after the bounce, the initial shock wave stals on the way because the energy is used up during the propagation. After the core bounce, the shock wave must propagate through the Fe core up to its surface against the falling material of outer layers. The energy loss occurs due to Fe dissociation during the propagation. Although the shock wave is launched up to $\sim 150$ km, it stalls without success in the spherical simulations. Looking at the energy budget, the initial energy of the shock wave amounts to several $10^{51}$ erg by the gravitational energy of inner core. The energy loss, on the other hand, due to the Fe dissociation amounts to minus several $10^{51}$ erg. Since this loss uses up the initial energy, the hydrodynamical explosion in $\sim 100$ ms is not possible.

Additional assistance to bring the energy of $10^{51}$ erg are necessary to revive the stalled shock wave. The neutrino heating mechanism behind the stalled shock wave is one of the plausible scenarios. At $\sim 100$ ms after the core bounce, the stalled shock wave is hovering around 200 km with accretion of outer layers (Figure 1, left). At center, the proto-neutron star is born already and emits abundant neutrinos from its hot and lepton rich core. A part of them hit the material just below the shock wave and are absorbed by nucleons (and nuclei). This contributes to the heating through the energy transfer from the neutrinos to the matter. This heating energy amounts to several $10^{51}$ ergs, which is comparable to the other factors described above. The size of this effect depends in detail on the shock wave dynamics, the energy and flux of neutrinos, the amount of the target material and duration time. In order to examine this process precisely, one has to solve the neutrino transfer together with the hydrodynamics. Modern numerical simulations must clarify whether the neutrino heating mechanism can revive the stalled shock wave as seen originally in the explosion by Bethe & Wilson (1985) via the delayed explosion mechanism.

2.3. Multi-dimensions with supercomputing technology
In addition to the role of neutrinos, novel features in multi-dimensional simulations are pivotal in the supernova mechanism. These are also challenging problems, which need the
Figure 1. (Left) Schematic diagram of the deformed shock wave and neutrino heating. (Right) Neutrino distributions in a supernova core evaluated by neutrino transfer in 3D.

latest technology of supercomputers. When one breaks the symmetry from 1D (spherical) to 2D (axial) and 3D in the numerical simulations, there are always new findings on the explosion mechanism due to hydrodynamical instabilities such as convections and standing accretion shock instabilities (SASI) (Blondin et al. 2003). Moreover, the importance of asymmetry is supported by the observational facts on the asymmetric properties of supernova remnants. The main idea is the combination of the neutrino heating and the hydrodynamical instabilities. Because of the asymmetric launch of the shock wave (ex. up/down asymmetric), the shock wave along a certain direction reaches up to a larger distance than that realized in 1D. The neutrino heating below the deformed positions of the stalled shock wave helps to push the further propagation (Figure 1, left). The main gain is the sufficient amount of time for neutrino heating, since the advection time for the accretion of material becomes longer than the 1D case.

It is to be noted that solving neutrino radiation-hydrodynamics is necessary to clarify this problem. Radiation-hydrodynamics in multi-dimensions is generally a difficult problem in astrophysics and engineering. Along with the advance of supercomputers, there is step-by-step progress in the numerical treatment of neutrino-radiation hydrodynamics. In 1D (spherical symmetry), it is possible to perform the first-principle-type calculations (Rampp et al. 2000, Liebendörfer et al. 2001, Sumiyoshi et al. 2005). However, no explosion is found in the numerical simulations of various research groups for typical progenitors. In 2D, state-of-the-art simulations with detailed neutrino and nuclear physics produce a dozen of explosion cases (See Table 1 in Kotake 2012b). However, they have been done with approximate treatment of neutrino transfer. Although the neutrino heating mechanism is promising in most of the 2D simulations, there are also plausible scenarios under discussion. In order to determine the most dominant effect, further systematic studies in 2D are necessary.

Whether this kind of multi-dimensional effects remains important in 3D is the current topics in supernova studies. The advantage of 3D extensions over 2D models have been discussed in the systematic analysis by a simplified model (Nordhaus et al. 2010) but remains controversial with new results (Hanke et al. 2012). There will be also new instabilities, which is hidden in 2D but appear in 3D. With the rapid progress of supercomputing technology, it became recently to perform the first 3D simulation starting from the collapse of a massive star. Takiwaki et al. have studied the 3D core-collapse supernovae by the ray-by-ray approach with the IDSA approximation (Takiwaki et al. 2012). Explosions are found in 3D modeling with 3D motion of convection and deformed propagation of shock wave. However, it is still premature to conclude the intrinsic 3D
effects since they have to perform more simulations with higher resolutions. One of the largest 3D simulations is running at the K-computer at Kobe, Japan, which has a peak speed of 10 PetaFLOPS (the world’s 2nd fastest machine as of June 2012).

It is also necessary to replace approximate treatment of the neutrino transfer to the accurate one. It has been a formidable task to solve the neutrino-radiation transfer in 3D space since it is a 6D phase-space problem. Recently there is remarkable achievement to solve the 6D Boltzmann equation for neutrino distributions (Sumiyoshi & Yamada 2012) in supernova cores (Figure 1, right; see also Kotake et al. 2012a). Future ExaFLOPS supercomputers will enable full 3D simulations of neutrino-radiation hydrodynamics of core-collapse supernovae.

3. Toward the birth of pulsars

Until we get the solid mechanism for the successful explosion, one needs to assume explosions for astrophysical applications such as nucleosynthesis by parameterizing the shock wave launch. There are a number of applications to explore the neutron star properties after the supernova explosion.

By putting initial condition of a proto-neutron star born in supernovae, it is possible to follow the thermal evolution of the proto-neutron star through the cooling by emission of neutrinos (e.g. Pons et al. 1999). By predicting the neutrino spectra, average energies and luminosities as a function of time, one can explore the EOS influence as well as the dependence on the properties of proto-neutron stars. These are also important templates of supernova neutrino bursts for future detection of the next galactic supernova. The neutrino signals from the collapse of massive stars have been systematically studied including the case of black hole formations (e.g. Sumiyoshi et al. 2007). Their evaluation of spectra has been applied to predict the event numbers (Nakazato et al. 2010b) at the current and future facilities of neutrino detection (Kistler et al. 2011).

There have been studies of pulsar kicks and rotations through simulation of the parameterized explosion after the bounce (e.g. Blondin & Mezzacappa 2007). For example, Wongwathanarat et al. (2010) have studied the pulsar kicks and rotations by following the motion of accretion and ejecta, to predict the velocity of neutron stars through momentum conservation and gravitational pulls. They obtain the time evolution of pulsar kicks and angular momentum, and find a moderate number of ~300 km/s for kick velocities and ~600 ms for spin periods. In principle, it is necessary to connect this kind of outcome with the progenitor mass and rotations via full supernova simulations.

In summary, the study of core-collapse supernovae is fascinating with multi-physics from femto- to kilometer scales. It is a challenging problem regarding extreme conditions, counter-acting 1% effects of neutrinos and multi-dimensions. Understanding the mechanism of supernova explosions requires neutrino-radiation hydrodynamics in three dimensions. Implementation of microphysics on nuclear data into the numerical simulation is mandatory. With the progress of supercomputing resources, there are promising 2-D cases of explosions. The current challenge is the 3D numerical simulations to solve the neutrino-radiation hydrodynamics on the latest and future technology of supercomputers. These numerical challenges are indispensable for clarifying the essential cause of supernova dynamics, and to answer the birth of pulsars from the gravitational collapse of massive stars.

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How “free” are free neutrons in neutron-star crusts and what does it imply for pulsar glitches?

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Abstract. The neutron superfluid permeating the inner crust of mature neutron stars is expected to play a key role in various astrophysical phenomena like pulsar glitches. Despite the absence of viscous drag, the neutron superfluid can still be coupled to the solid crust due to non-dissipative entrainment effects. Entrainment challenges the interpretation of pulsar glitches and suggests that a revision of the interpretation of other observed neutron-star phenomena might be necessary.

Keywords. stars: neutron, dense matter, equation of state, gravitation, hydrodynamics, stellar dynamics, (stars:) pulsars: general, stars: rotation

1. Introduction

Pulsars are among the most accurate clocks in the universe, the delays associated with their spin-down being at most of a few milliseconds per year. Nevertheless, some pulsars have been found to exhibit sudden increases in their rotational frequency $\Omega$. These “glitches”, whose amplitude varies from $\Delta\Omega/\Omega \sim 10^{-9}$ up to $10^{-5}$ (see e.g. Section 12.4 in Chamel & Haensel 2008). The long relaxation times following the first observed glitches and the glitches themselves hinted at the presence of superfluids in neutron-star interiors (Baym et al. 1969, Packard 1972). In fact, neutron-star superfluidity had been predicted by Migdal (1959) based on the microscopic theory of superconductivity developed by Bardeen, Cooper and Schrieffer two years earlier. Subsequently Ginzburg & Kirzhnits (1964) estimated the critical temperature for neutron superfluidity and suggested that the interior of a neutron star could be threaded by an array of quantized vortices. Anderson & Itoh (1975) advanced the seminal idea that pulsar glitches are triggered by the sudden unpinning of such vortices in the neutron-star crust. Their scenario found some support from laboratory experiments in superfluid helium (Campbell 1979, Tsakadze & Tsakadze 1980). Further developments aimed at explaining the post-glitch relaxation by the motion of vortices (Pines & Alpar 1985, Jones 1993). In the meantime, Alpar et al. (1984) argued that the core of a neutron star (supposed to contain superfluid neutrons and superconducting protons) is unlikely to play any role in glitch events. Large pulsar glitches are still usually interpreted as sudden transfers of angular momentum between the neutron superfluid in the crust and the rest of the star. The confidence in this interpretation comes from i) the regularity observed in many glitching pulsars and ii) the fact that the estimated ratio of the moment of inertia $I_s$ of the superfluid component driving glitches to the total stellar moment of inertia $I$ is about $I_s/I \sim 1 - 2\%$ at most, as expected if only the crustal superfluid is involved (Link et al. 1999).
2. Crustal entrainment

Even though the neutron superfluid in the crust can flow without friction, it can still be entrained by nuclei, as first shown by Carter et al. (2005). Indeed, unbound or “dripped” neutrons can be Bragg reflected by the crustal lattice in which case they cannot propagate and are therefore trapped in the crust. Unlike viscous drag, this entrainment effect is non-dissipative. Neutron diffraction is a well-known phenomenon, which has been routinely exploited to probe the structure of materials. Unlike the neutron beams used in terrestrial experiments, neutrons in neutron-star crusts are highly degenerate. Due to the Pauli exclusion principle, they must all have different (Bloch) wave vectors. As a result, they are simultaneously scattered in different directions. The strength of entrainment is therefore determined by the way all unbound neutrons are diffracted. This can be characterized by the density $n_n^c$ of conduction neutrons, i.e. neutrons that are effectively “free” to move with a different velocity than that of nuclei. Equivalently, entrainment effects can be embedded in an effective neutron mass $m_n^明星 = m_n n_n^f / n_n^c$ where $m_n$ is the bare neutron mass and $n_n^f$ the density of unbound neutrons. Neutron conduction has been systematically studied in all regions of the inner crust using the band theory of solids (see Chamel 2012). The neutron superfluid has thus been found to be very strongly entrained by the crust, especially in the region with average baryon densities $\bar{n} \sim 0.02 - 0.03$ fm$^{-3}$.

3. Implications for pulsar glitches

According to a popular interpretation, pulsar glitches are due to sudden transfers of angular momentum between the neutron superfluid permeating the crust and the rest of the star. Due to entrainment, the angular momentum $J_s$ of the superfluid depends not only on the angular velocity $\Omega_s$ of the superfluid, but also on the (observed) angular velocity $\dot{\Omega}$ of the star and can be expressed as (see Chamel & Carter 2006)

$$J_s = I_{ss} \Omega_s + (I_s - I_{ss}) \dot{\Omega},$$

(3.1)

Chamel & Carter (2006) showed that the product of the fractional moments of inertia $I_s/I$ and $I_s/I_{ss}$ should obey the following constraint

$$\frac{(I_s)^2}{II_{ss}} \geq \mathcal{G}, \quad \mathcal{G} = \frac{1}{t} \sum_{i} \frac{\Delta \Omega_i}{|\dot{\Omega}|},$$

(3.2)

where the sum is over all glitches observed during the time $t$ and $\dot{\Omega}$ is the observed average pulsar spin-down rate. A statistical study of glitching pulsars leads to $\mathcal{G} \simeq 1.7\%$ (see Lyne et al. 2000). If entrainment is neglected, $I_{ss} = I_s$ so that $J_s = I_s \Omega_s$ and $(I_s)^2/(II_{ss})$ reduces to $I_s/I$. Approximating this ratio by the fractional moment of inertia of the crust $I_{crust}/I$, the constraint (3.2) was found to be easily satisfied for any realistic equation of state yielding plausible values for the neutron-star mass $M$ and radius $R$ (see Link et al. 1999). On the other hand, taking entrainment into taken account (see Chamel), we have found that $(I_s)^2/(II_{ss}) \simeq 0.17 I_{crust}/I$. Observations of large pulsar glitches and (3.2) require that the fractional moment of inertia of the crust exceed $\sim 10\%$. The ratio $I_{crust}/I$ can be estimated using the approximate expression of Lattimer & Prakash (2000). The resulting fractional moment of inertia of the crust is shown in Fig. 1 for different neutron-star masses and radii using the neutron-star crust model of Onsi et al. (2008).

This analysis implies that very active glitching pulsars should have an unusually small mass, significantly below the canonical value of $1.4M_\odot$ ($M_\odot$ being the mass of our Sun). The existence of low mass neutron stars is not excluded, but such stars are not expected to be formed in a type II supernova explosion (see e.g. Strobel & Weigel 2001). Therefore,
4. Conclusions

Due to entrainment effects, the neutron superfluid in neutron-star crusts does not carry enough angular momentum to explain large pulsar glitches. On the other hand, Alpar et al. (1984) argued that the neutron superfluid in the core is also strongly coupled to the crust. The solution to this problem requires a closer examination of crustal entrainment and crust-core coupling. The presence of nuclear “pastas” at the crust bottom, quantum and thermal fluctuations of ions about their equilibrium positions, crystal defects, impurities and more generally any kind of disorder would presumably reduce the number of entrained neutrons. Further work is needed to confirm these expectations. However, Sotani et al. (2012) have recently argued that quasi-periodic oscillation observed in giant flares from soft gamma-ray repeaters restrict the existence of pastas (if any) to a very narrow crustal region. Moreover, observations of the initial cooling in persistent soft X-ray transients are consistent with a low level of impurities in the crust (see Shternin, Yakovlev & Haensel 2007, Brown & Cumming (2009)) and this level is unlikely to be higher in non-accreting neutron stars like Vela. Incidentally these observations provided another proof for crustal superfluidity. On the other hand, the strong crust-core coupling assumed here could be much weaker, especially if protons form a type II superconductor (see Sedrakian et al. 1995). The observed rapid cooling of the neutron star in Cassiopeia A has recently provided strong evidence for core neutron superfluidity and proton superconductivity, but not on its type (see Page et al. 2011, Shternin 2011). Link (2003) showed that type II superconductivity is incompatible with observations of long-period precession in pulsars. In the meantime, the work of Lyne et al. (2010) has cast some doubt on the interpretation of long-period precession. In fact, proton superconductivity might be neither of type I nor of type II (see Babaev 2009). In addition, neutron-star

![Figure 1](image_url)

**Figure 1.** Fractional moment of inertia of neutron-star crusts for different neutron-star masses (in solar masses) and radii. The horizontal dotted line indicates the lowest value consistent with Vela pulsar glitches.
cores might contain other particle species with various superfluid and superconducting phases (see e.g. Oertel & Buballa 2006). This warrants further studies. But if glitches are induced by the core of a neutron star, it will be challenging to explain the observed regularity of glitches and the fact that $G \lesssim 2\%$.

Acknowledgements

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Neutron star structure: what we learn from their masses and radii

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Abstract. Neutron stars possess the densest matter and strongest gravitational fields that are accessible to observations. In this talk, I will discuss how precise measurements of neutron star radii, masses, and spins not only open a window onto the poorly known neutron star interior but can also be used to probe their formation mechanism, their recycling to millisecond periods, and their connection to the formation of low-mass black holes.
Session 3

Pulsar Discovery II
Fermi-LAT searches for γ-ray pulsars

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Abstract. The Large Area Telescope (LAT) on the Fermi satellite is the first γ-ray instrument to discover pulsars directly via their γ-ray emission. Roughly one third of the 117 γ-ray pulsars detected by the LAT in its first three years were discovered in blind searches of γ-ray data and most of these are undetectable with current radio telescopes. I review some of the key LAT results and highlight the specific challenges faced in γ-ray (compared to radio) searches, most of which stem from the long, sparse data sets and the broad, energy-dependent point-spread function (PSF) of the LAT. I discuss some ongoing LAT searches for γ-ray millisecond pulsars (MSPs) and γ-ray pulsars around the Galactic Center. Finally, I outline the prospects for future γ-ray pulsar discoveries as the LAT enters its extended mission phase, including advantages of a possible modification of the LAT observing profile.

Keywords. pulsars: general, gamma rays: observations

1. Introduction

In the first four decades since their discovery, pulsars were almost the exclusive domain of radio (and to a lesser extent X-ray) astronomy. Indeed, of the ∼2000 known pulsars†, the majority were discovered in radio. Since June 2008, however, with the launch of the LAT, on the Fermi satellite, γ-rays have become a viable means of discovering (and studying) pulsars. More important than the number of LAT-detected pulsars (a small fraction of the overall population), the LAT sample is subject to different biases than the radio sample. LAT pulsars are typically nearby (∼few kpc) and energetic ( ˙E > 10^{33} erg s^{-1}), and a large fraction are radio-quiet. Furthermore, γ-rays, unlike the radio beams, carry a significant fraction of the rotational energy of pulsars, thus providing a powerful probe into these extreme objects. Finally, LAT pulsars provide a crucial input into our understanding of the overall neutron star population of the Galaxy.

The LAT is a pair conversion telescope consisting of a tracker, a calorimeter, and a segmented anti-coincidence detector, along with a programmable trigger and a complex data acquisition system. By incorporating the latest advances from particle physics‡, including the use of silicon-strip detectors, the LAT has achieved a giant leap in capabilities compared to its predecessor, EGRET. The LAT extends to higher energies (>300 GeV vs ∼10 GeV), has a larger effective area and field of view, improved angular and energy resolutions, and much lower deadtime (Atwood et al. 2009). In its first 4 years of operations, the LAT has collected >200 million “source” class events, compared to ∼1.5 million photons collected by EGRET, in its 9-year lifetime.

Regarding pulsars, the progress made by the LAT has been spectacular. The γ-ray pulsar population has grown from 7 firm detections (plus a few candidates) at the time

† http://www.atnf.csiro.au/research/pulsar/psrcat
‡ Bill Atwood was awarded the 2012 Panofsky Prize in Experimental Particle Physics “For his leading work on the design, construction, and use of the Large Area Telescope [...]”.

81
of the Fermi launch (Thompson 2008), to 117 detections in three years of LAT survey observations (The Second Fermi-LAT Catalog of γ-ray Pulsars, in preparation). Beyond the jump in the number of pulsars, the increased statistics enable detailed (e.g. phase-resolved) studies on individual pulsars, previously out of reach. The LAT has also opened up the unexplored 10–100 GeV window. EGRET detected a mere handful of >10 GeV photons from the brightest pulsars (Thompson 2005), whereas the LAT detects significant emission from over two dozen pulsars in this energy range and even >25 GeV pulsations from the brightest ones (e.g. Crab, Vela, Geminga, see Saz Parkinson 2012).

Of the 117 LAT detections, 61 pulsars were known prior to Fermi. Pulsations were obtained by folding the γ-rays with a radio (or X-ray) timing model. Of these 61, 20 are MSPs (e.g. Abdo et al. 2009c), a hitherto unknown class of strong γ-ray emitters. More surprisingly, a large number of MSPs (>40) were discovered in radio searches of LAT unassociated sources (Ray et al. 2012). Most (20 so far, e.g. Ransom et al. 2011) will likely exhibit γ-ray pulsations†, once enough data and/or a precise timing model is obtained (usually from radio observations). Finally, 36 of the 117 γ-ray pulsars were discovered directly in blind searches of LAT data (Abdo et al. 2009b, Saz Parkinson et al. 2010, Saz Parkinson 2011, Pletsch et al. 2012a, Pletsch et al. 2012b). The rest of this paper discusses the challenges, results, and prospects of these searches.

2. Blind searches for γ-ray pulsars (compared to radio)

Two factors make γ-ray searches for pulsars particularly challenging, compared to radio searches. The first involves the scarcity of events. The LAT detects ∼1 γ-ray per day from a typical (bright) pulsar. This means that LAT searches for pulsars span months to years (see Figure 1). The second complication involves the broad, energy-dependent PSF of the instrument (from ∼5° at 100 MeV to ∼0.2° at 100 GeV, 68% containment, normal incidence). This results in significant source confusion, especially in high background regions like the Galactic plane, where the diffuse γ-ray emission makes it hard to resolve individual sources. Essentially, it is impossible to select, with certainty, events coming from a source, so statistical techniques must be employed. Using these techniques, it is possible to determine the probability that each event is coming from the source of interest and improve the sensitivity of the search by assigning a weight to each event equal to this probability (Kerr 2011).

Searches over long (sparse) data sets make standard FFT techniques impractical. To tackle this problem, Atwood et al. (2006) developed the “time-differencing technique” and applied it successfully to EGRET data (Ziegler et al. 2008). The core of the technique involves computing the FFT of the differences between the times of events (up to a maximum, sliding, time window), rather than using the original time series. Using a time window of ∼weeks significantly alleviates the coherence requirements of the search.

2.1. Young pulsars

Within weeks of the launch of Fermi, the first radio-quiet γ-ray pulsar was discovered in the supernova remnant CTA 1 (Abdo et al. 2008). This was followed by many more discoveries (e.g. Abdo et al. 2009b, Saz Parkinson et al. 2010). Many of these early γ-ray pulsars discovered by the LAT are coincident with old EGRET unidentified sources. Many, like the pulsar in CTA 1, are also coincident with known supernova remnants or pulsar wind nebulae, and were thus long suspected of hosting pulsars (e.g. PSR J1836+5925, J2021+4026). Radio follow-up observations of the LAT-discovered pulsars showed that

† Given that they are LAT γ-ray sources selected precisely for their pulsar-like qualities.
most of them are radio-quiet (or extremely radio-faint), suggesting that the γ-ray emission originates far from the neutron star surface, resulting in broad beams. It is now clear that these radio-quiet γ-ray pulsars represent a significant fraction of the neutron star population of the Galaxy (see Guillemot et al. (2012), in these proceedings, for a detailed review of the radio observations of LAT γ-ray pulsars). All 36 pulsars found in LAT blind searches to date are young (\( \tau < 1 \times 10^7 \) yr) energetic (\( 10^{33} \text{ erg s}^{-1} < \dot{E} < 10^{37} \text{ erg s}^{-1} \)) pulsars with frequencies below \(~20 \) Hz. These pulsars often exhibit timing irregularities, in the form of timing noise and glitches. Since most are not detected in radio, the LAT is the only instrument capable of timing them (Ray et al. 2011). While it is possible to time these noisy (or “glitchy”) pulsars, a good timing model often requires many frequency derivatives and other whitening terms, making their discovery over long data spans extremely challenging. Searches for these pulsars may only be possible over LAT observing periods lasting ~months, rather than years (see Figure 2).

2.2. Millisecond pulsars

As mentioned above, the discovery of γ-ray MSPs (Abdo et al. 2009c) was largely unexpected. Equally unexpected was the large number of MSPs discovered by radio telescopes searching LAT unassociated sources (Ray et al. 2012). This fact, combined with the large fraction of radio-quiet young pulsars, raises the question of whether large numbers of radio-quiet γ-ray MSPs remain to be discovered in blind searches of LAT data. The answer, from examining the identified γ-ray sources in the almost flux-limited Fermi-LAT Bright Source List (Abdo et al. 2009a), appears to be no. Whereas at least two thirds of young γ-ray pulsars are radio quiet, at most one third of γ-ray MSPs are (Romani 2012).

Blind searches for MSPs are vastly more complicated than searches for young pulsars. Firstly, a majority (~80%) of MSPs are in binary systems, and a full blind search over unknown orbital parameters is out of reach given current computer capabilities. Searches for isolated MSPs are possible, but the high frequencies increase the memory and CPU requirements. Positional uncertainties become more relevant with increasing frequencies and the typical tolerance of a blind search using several years of data is of order a
fraction of an arc second. This means that one must either perform a fine scan over the LAT positions, or else identify a precise position of a plausible counterpart, using multi-wavelength (e.g. X-ray) observations. A number of LAT sources have been identified as promising pulsar candidates, by virtue of their variability and spectral properties (Ackermann et al. 2012). More recently, X-ray and optical studies of some of the brightest of these have identified some strong “black widow” candidates: eclipsing binary MSPs with very compact, almost circular orbits, where the pulsar is destroying its low-mass companion (Romani & Shaw 2011, Romani 2012). These studies derive extremely precise positions (to ∼ 0.1") and stringent constraints on two out of the three requisite orbital parameters (leaving only the projected semi-axis relatively unconstrained). Thus, for the first time, searches for such binary MSPs using γ-ray data are possible. A deep LAT search of 2FGL J2339.6+0532 (the most promising of these “black widow” candidates) unfortunately produced no significant candidate, but further efforts are in progress (see Belfiore 2012 for details).

3. Searches for pulsars around the Galactic Center

Understanding the γ-ray emission from the Galactic Center (GC) region is both challenging and controversial. Claims that γ-ray emission from the GC may be related to dark matter (e.g. Hooper & Goodenough 2011, Weniger 2012) should be measured up against more conventional explanations, such as a possible origin from γ-ray pulsars. As a site of massive star formation, it likely contains thousands of pulsars, but their radio detection is hampered by the large amount of interstellar scattering. Nevertheless, some pulsars have been discovered fairly close to the GC, and predictions for the number of

![Figure 2. Blind-search significance of PSR J1023-5745, as a function of the cumulative observing time. Initially, the significance increases with time, but after a period of 7-10 months, the significance peaks and then decreases with the addition of more data.](image-url)
radio pulsars that could be associated with the GC range in the thousands (Deneva et al. 2009). It is possible that some of the undiscovered pulsars in the region are radio quiet, like the majority of young pulsars found in LAT blind searches (e.g. PSR J1732-3131, see Figure 3).

Blind searches for γ-ray pulsars around the GC are affected by low fluxes (due to the large distance), and high levels of diffuse emission. Indeed, most LAT pulsars are likely nearby (~few kpc). The LAT has, however, detected pulsations from MSP J1823-3021A, in the globular cluster NGC 6624, at 8.4 kpc (roughly the distance to the GC). It is possible to estimate how far blind searches might be sensitive out to. From scaling arguments, considering that the γ-ray flux of the Crab is several thousand times brighter than the faintest γ-ray pulsar discovered in a blind search, we conclude that it is possible to discover a Crab-like γ-ray pulsar in a LAT blind search out to at least ~15 kpc.

Perhaps the biggest complication in searching for faint pulsars around the GC is the fact that such a pulsar may be young and noisy (or “glitchy”). As described above, the loss of coherence of the signal limits the amount of data that can be effectively searched (see Figure 2). Thus, regardless of the number of years of LAT data available, it may only be possible to search several months at a time. Thus, the sensitivity of searches in this region may only improve significantly with improvements in reconstruction (e.g. Pass 8, see Baldini 2011, Fermi Symposium), or a change in the observing mode. For the first four years of its mission, Fermi has operated mostly in survey mode. This has many advantages for most of the scientific goals of the mission, including pulsar searches (and timing). Modifying the observing profile, however, could enhance the sensitivity to detection of faint signals (both from pulsars and/or dark matter) from the GC. Figure 3 (right) shows the relative gain in exposure (compared to survey mode) with a modified mode in which the LAT points to a location slightly offset from the GC. Whenever the GC is occulted, the LAT could go back into survey mode, thus maintaining some level of exposure over the entire sky.

Figure 3. Left: LAT view of the GC (Porter, 2011 Fermi Symposium). The bright source at the GC (2FGL J1745.6-2858) is curved and non-variable, like most LAT pulsars. Right: Relative exposure (compared to survey mode) with a LAT viewing strategy favoring the GC. The gain in exposure is a factor of ~3, while the exposure for other parts of the sky decreases to roughly one third, in the worst case.

4. Conclusions and Prospects

The NASA Senior Review recently recommended that Fermi operations continue through 2016. In principle, Fermi could continue to operate well beyond this date†. As the LAT ac-

† Unlike its predecessor, EGRET, the LAT has no consumables that limit its lifetime.
cumulates more data, it will detect γ-ray pulsations from ever fainter radio-loud pulsars. As for blind searches of γ-ray data, they too will continue to produce new discoveries, although the increasing computational demands will require additional resources (e.g., Einstein@Home) and efficient computational techniques to exploit them. Finally, multi-wavelength observations (radio, X-rays, and optical), will continue to play a crucial role in LAT pulsar studies, especially in facilitating the search for more exotic pulsar systems, such as “black widow” systems, young binary pulsars, and pulsars around the GC. In this last case, a modified observing profile enhancing the exposure to this region (by a factor of ~3) could play a crucial role in future discoveries.

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Radio counterparts of gamma-ray pulsars

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Abstract.
Observations of pulsars with the Large Area Telescope (LAT) on the Fermi satellite have revolutionized our view of the gamma-ray pulsar population. For the first time, a large number of young gamma-ray pulsars have been discovered in blind searches of the LAT data. More generally, the LAT has discovered many new gamma-ray sources whose properties suggest that they are powered by unknown pulsars. Radio observations of gamma-ray sources have been key to the success of pulsar studies with the LAT. For example, radio observations of LAT-discovered pulsars provide constraints on the relative beaming fractions, which are crucial for pulsar population studies. Also, radio searches of LAT sources with no known counterparts have been very efficient, with the discovery of over forty millisecond pulsars. I review radio follow-up studies of LAT-discovered pulsars and unidentified sources, and discuss some of the implications of the results.

Keywords. pulsars: general, gamma rays: observations

1. Introduction

The Large Area Telescope (LAT), a pair conversion telescope sensitive to gamma-ray photons with energies between 20 MeV and more than 300 GeV, is the primary instrument on the Fermi observatory launched in June 2008. The LAT is the most sensitive GeV telescope to have ever flown, it has a large field of view of 2.4 sr, and it operates in a continuous sky survey mode so that it covers the entire sky every two orbits (\(\sim 3\) hours). These characteristics make the LAT an ideal instrument for studying pulsars in the GeV domain, and they have also led this instrument to provide the most complete picture of the gamma-ray sky to date.

GeV pulsar observations have been one of the main successes of the LAT. After three years of LAT data taking, the number of pulsars known to emit in gamma rays has increased from less than ten objects (e.g. Thompson 2001) to 117 pulsars detected with high significance\textsuperscript{†}. Gamma-ray pulsars are currently roughly split into three categories of comparable size: one third are “normal” radio pulsars, another third are “normal” pulsars discovered through blind searches of the LAT data (see Saz Parkinson, these proceedings, for a review of blind search techniques and main results), and a third are radio “millisecond” pulsars (MSPs). Most of these pulsars have been detected in the gamma-ray data using ephemerides obtained from radio timing observations, conducted over several months to several years (Smith et al. 2008).

\textsuperscript{†} A public list of LAT-detected pulsars is available at: https://confluence.slac.stanford.edu/display/SCIGRPS/Detected+Gamma-Ray+Pulsars
The Second Fermi Large Area Telescope Catalog of gamma-ray pulsars, currently in preparation within the Fermi collaboration, will list the properties of the 117 pulsars detected in the first three years of LAT operation.
Radio pulsar observations in support of the Fermi mission have also been useful for determining which of the LAT-discovered pulsars also emit in radio, which provides important information about the geometry of emission in the pulsar magnetosphere, and also for determining the nature of certain Fermi LAT sources with no known associations (so-called “unassociated sources”). Radio pulsar searches in unassociated LAT sources have indeed led to the discovery of many new pulsars, including a large fraction of radio MSPs in binary orbits.

In these proceedings I review radio observations of pulsars discovered in blind searches of the LAT data and searches for radio pulsars at the position of LAT unassociated sources, and discuss some implications of the results in terms of radio and gamma-ray beaming of pulsars.

2. Radio detections of blind search pulsar discoveries

A total of 36 pulsars have so far been discovered in blind searches of the LAT data (Abdo et al. 2009, Saz Parkinson et al. 2010, Saz Parkinson 2011, Pletsch et al. 2012a, Pletsch et al. 2012b). Following these discoveries, systematic searches for radio pulsations from these pulsars have been conducted at several large radio telescopes around the world (see e.g. Ray et al. 2011). Detections or non-detections of radio emission from gamma-ray pulsars provide information on the emission geometry in their magnetosphere, and also useful constraints on the radio and gamma-ray beaming fractions, which are critical for population studies. The searches for radio emission resulted in the detection of four of the LAT-discovered pulsars (Camilo et al. 2009, Abdo et al. 2010, Pletsch et al. 2012a). A tentative detection of 10 aligned sub-pulses from a fifth pulsar at 34.5 MHz was reported by Maan et al. (2012), but additional searches are needed due to the low statistical significance of the result. Stringent upper limits on the radio fluxes of the other pulsars were also placed.

The fluxes of the radio-detected LAT-discovered pulsars scaled to 1400 MHz are displayed in Figure 1a. Two of them, PSRs J1741−2054 and J2032+4127, have fluxes that are relatively common among other normal radio pulsars. On the other hand, PSRs J0106+4855 and J1907+0602 have extremely low values of the radio flux, similar to those of the faintest previously-known pulsars. The upper limits on the radio fluxes of the other new gamma-ray pulsars, also shown in Figure 1a, indicate that their radio fluxes are at most in the same order as those of PSRs J0106+4855 and J1907+0602. It is clear that Fermi made the discovery of the 36 blind search pulsars significantly easier.

For pulsars detected in radio, one can determine the dispersion measure (DM), corresponding to the quantity of free electrons along the line-of-sight, which in turn can be used to determine distances to the pulsars, via a model for the distribution of free electrons in the Galaxy (e.g. NE2001; see Cordes & Lazio 2002). In turn, these distance estimates can be used to derive radio or gamma-ray pseudo-luminosities for these pulsars, which is impossible in the absence of any distance information. Figure 1b shows the pseudo-luminosities of the LAT-discovered pulsars detected in radio. As can be seen from this plot, three of the four radio-detected pulsars have extremely low radio pseudo-luminosities compared to the rest of the normal pulsar population. Understanding the causes of non-radio-detections of the majority of the LAT-discovered pulsars as well as understanding the very low luminosities of the radio-detected ones will be of paramount importance for pulsar population studies.
Figure 1. **Top:** radio flux density at 1.4 GHz, $S_{1400}$, as a function of the characteristic age, $\tau = P/(2\dot{P})$ for the normal population of pulsars. Black dots represent radio pulsars from the ATNF catalog (Manchester et al. 2005), and colored symbols represent pulsars discovered in blind searches of Fermi LAT data, later detected in the radio domain. Upper limits on the radio flux density of other LAT blind searches pulsars are shown as blue arrows. **Bottom:** radio pseudo-luminosity, $S_{1400}d^2$, as a function of $\tau$, for the same pulsar sample.

3. Radio MSP discoveries in Fermi sources

In addition to searches for radio emission from LAT-discovered pulsars, radio telescopes have also conducted deep searches for pulsations from Fermi LAT sources with no known associations. These unassociated sources are numerous: they represent $\sim30\%$ of the 1451 sources listed in the Fermi LAT Second Source Catalog (2FGL; Nolan et al. 2012), and among this source category, a large fraction have gamma-ray emission properties reminiscent of those of known pulsars, i.e., low gamma-ray flux variabilities and significant curvature in their emission spectra (cf. Figure 17 of Nolan et al. 2012), in contrast with e.g. blazars and other active galactic nuclei (see e.g. Lee et al. (2012) or Ackermann et al. (2012) for examples of Fermi LAT source classification studies). Radio pulsar searches of Fermi LAT sources therefore offered the possibility to reveal the nature of some of the LAT unassociated sources with pulsar properties.

Searches for pulsars in unidentified high-energy sources had already been conducted prior to the Fermi mission: for instance, pulsars have been searched in EGRET sources, with limited success as searches were complicated by the large number of radio pointings.
Figure 2. Map of the gamma-ray sky as seen with the Fermi LAT in Galactic coordinates, with the locations of the 43 radio MSPs discovered in searches for pulsars in Fermi unassociated sources. MSPs discovered at the GBT are shown in blue, while pulsars found with the GMRT are in green, Effelsberg in black, Parkes in red, and Nançay in magenta. PSR J1103−5403 is represented with a different symbol as it has been shown not to be associated with the LAT source in which it was found (Keith et al. 2011).

required to cover a typical gamma-ray source (see for instance Champion et al. 2005 or Crawford et al. 2006). In contrast, Fermi LAT sources are typically localized to within 10′ due to the improved angular resolution (Nolan et al. 2012). Large radio telescopes having beam widths comparable to this localization accuracy, they can cover Fermi LAT sources in only one or a few pointings, making these searches easier and more efficient.

Radio pulsar searches in LAT unassociated sources undertaken so far have led to the discovery of 43 new radio MSPs, and an additional four normal pulsars (e.g. Ransom et al. (2011), Keith et al. (2011), Guillemot et al. (2012); a full listing of pulsar discoveries in Fermi sources to date with complete references is available in Ray et al. 2012). The locations of MSPs found in these surveys are displayed in Figure 2. It is apparent that the new MSPs are widely distributed in Galactic latitudes, which have been only modestly surveyed in past radio pulsar searches with sensitivity to this type of pulsars. These new MSPs are observed to have somewhat different properties than the previously known MSP population in the Galactic disk: for instance, at least 10 “black widow” and four “redback” systems have been discovered in Fermi LAT sources, while only three black widows and one redback were known in the Galactic disk prior to Fermi’s launch (see Roberts (2011) and references therein). Another difference is the period distribution of the new MSPs, observed to be concentrated toward smaller values than those of previously-known Galactic disk MSPs (see Figure 4 of Ray et al. 2012). It is thus clear that pulsar searches in Fermi LAT sources are biased in a different way than traditional radio surveys, and thus help to get a more complete picture of the population of MSPs in the Galaxy.

The new MSPs have been timed at radio wavelengths following their discovery, and as they became available the timing parameters obtained from these measurements have been used to phase-fold the LAT data. Because the MSPs were found within the error boxes of LAT sources, these searches unsurprisingly resulted in the detection of gamma-ray pulses in most cases, one counter-example being PSR J1103−5403, discovered coincidentally in a source likely powered by an active galactic nucleus (Keith et al. 2011).

Unlike several of the LAT-discovered pulsars detected in radio, these new MSPs are not particularly faint and would have eventually been found by current or future radio pulsar
surveys. However, the Fermi LAT accelerated their discovery by guiding radio telescopes to the pulsar-like sources in which they were found, which enabled quicker inclusions of these MSPs in pulsar timing arrays aiming at detecting low frequency gravitational waves (a review of pulsar timing array projects can be found in Hobbs, these proceedings). Furthermore, unassociated sources are often searched for pulsars multiple times, as binary eclipses or bad scintillation states can prevent detection on particular epochs. Such multiple re-observations are generally impossible in standard surveys, which are time-limited. This factor also likely contributed to the many MSP discoveries in Fermi LAT unassociated sources.

Contrasting with the many radio MSP discoveries, only four normal radio pulsars have been discovered within the error boxes of Fermi LAT sources, all of them at low Galactic latitudes. One of them, PSR J2030+3641, has been detected as a pulsed gamma-ray emitter since its discovery (Camilo et al. 2012). As is discussed in Camilo et al. (2012), this is likely due to the fact that past surveys of the Galactic plane have found most of the detectable normal pulsars. Based on the small number of radio pulsar detections in low Galactic latitude gamma-ray sources, and the fact that most of the LAT-discovered pulsars are undetected in radio, they also proposed that the many unassociated gamma-ray sources with pulsar properties remaining near the plane are indeed pulsars, with little or no radio emission emitted toward the Earth. Continued blind searches are therefore important for revealing the nature of these low Galactic latitude gamma-ray sources.

4. Radio and gamma-ray beaming

A large fraction of normal gamma-ray pulsars are radio-quiet. Are there radio-quiet gamma-ray MSPs? Blind searches for MSPs in the LAT data are complicated by the fact that most known MSPs are in binary systems (∼80% of them), unlike normal pulsars, which are almost all isolated. In the absence of any constraints on the orbital parameters, blind gamma-ray searches for binary MSPs are intractable with the current computational resources, as the number of parameters to be tested is too large. It is nevertheless possible to search for isolated MSPs in the LAT data, with the same techniques as the ones used for searching for normal isolated pulsars. Until now, such searches have failed to find any new isolated gamma-ray MSPs (e.g. Pletsch et al. 2012a).

The fact that no MSP has so far been found in blind searches of the LAT data, and that all known gamma-ray MSPs are therefore radio-loud, suggests that most gamma-ray MSPs must be detectable in radio. Statistics of the current population of gamma-ray sources corroborate this observation: selecting 249 bright sources from the 2FGL catalog, Romani (2012) noted that 12 sources are radio-loud MSPs, and that only six sources remain unassociated, thanks to all source identification efforts, including blind pulsar searches in radio and in gamma rays. One can draw the following conclusion: even if all of the six unassociated sources are radio-quiet MSPs, then the majority of gamma-ray MSPs in this sample are radio-loud. Among these six unassociated sources, the high Galactic latitude objects 2FGL J1311.7−3429 (Romani 2012, Kataoka et al. 2012) and J2339.6−0532 (Romani 2011, Kong et al. 2012) have clear pulsar-like gamma-ray properties and could therefore host radio-quiet MSPs. Multi-wavelengths studies of these objects have led to the discovery of optical and X-ray counterparts, exhibiting strong modulations of their emission with periods of ∼1.56-hr and ∼4.63-hr respectively. These systems are likely to be black widow-type MSPs. The constraints on the orbital parameters as well as the precise positions of these objects obtained from these measurements could make blind gamma-ray pulsation searches feasible for these objects (blind gamma-ray search efforts of such systems are presented in Belfiore, these proceedings).
Based on the same sample of 249 bright 2FGL sources, Romani (2012) showed that most normal gamma-ray pulsars selected are radio-quiet. Unlike MSPs, normal pulsars thus seem to have smaller radio beams than gamma-ray beams. Nevertheless, as was shown by Ravi et al. (2010), the most energetic objects among normal gamma-ray pulsars are all radio-loud, while the fraction of radio-loud pulsars rapidly decreases for less energetic objects. This suggests an interesting correlation between the size of the radio beam and the pulsar properties. Such constraints on the respective sizes of radio and gamma-ray beams for the different pulsar families provide key input for pulsar population studies, underlining the importance of joint radio and gamma-ray observations of pulsars.

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Session 4

Pulsar diversity
Rotating Radio Transients and their place among pulsars

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Abstract. Six years ago, the discovery of Rotating Radio Transients (RRATs) marked what appeared to be a new type of sparsely-emitting pulsar. Since 2006, more than 70 of these objects have been discovered in single-pulse searches of archival and new surveys. With a continual inflow of new information about the RRAT population in the form of new discoveries, multi-frequency follow ups, coherent timing solutions, and pulse rate statistics, a view is beginning to form of the place in the pulsar population RRATs hold. Here we review the properties of neutron stars discovered through single pulse searches. We first seek to clarify the definition of the term RRAT, emphasising that “the RRAT population” encompasses several phenomenologies. A large subset of RRATs appears to represent the tail of an extended distribution of pulsar nulling fractions and activity cycles; these objects present several key open questions remaining in this field.

Keywords. pulsars: general, stars: neutron, stars: statistics

1. The discovery of and interest in RRATs
Pulsars were originally discovered through their single pulse emission (Hewish et al. 1968). However, periodicity-based search techniques later dominated major pulsar search efforts due to the drastic gain in sensitivity they provided to typical pulsar signals (e.g. Manchester et al. 2001). A recent renewal of interest in single pulse searches led McLaughlin et al. (2006) to uncover sporadic pulses from eleven neutron stars whose signal was not detectable through periodicity searches in their 35-minute observations. These objects were dubbed Rotating Radio Transients (RRATs), and since 2006, single-pulse searches of archival and new pulsar surveys have revealed more than 60 further examples of such objects (e.g. Deneva et al. 2009; Keane et al. 2010; Burke-Spolaor et al. 2011).

If all RRATs’ sporadically-detectable emission arises from nulling, the net Galactic population of these objects may be equal to or greater than that of steadily-emitting radio pulsars, generating a substantial discrepancy between neutron star birthrates and core-collapse supernova (CCSN) rates (Keane & Kramer 2008). This has given rise to questions about the intrinsic nature of RRATs, and how their observed behaviour may link to other pulsar populations or to a cycle in normal pulsar evolution. Motivated by this, below we make explicit what is meant by the term “RRAT,” and review what studies are revealing about these objects’ relationship to other neutron star populations.

2. Defining the RRAT
2.1. RRAT as a survey definition
In recent papers reporting pulsar survey results, the most common definition of RRAT applies to a pulsar that was discovered in single pulses, but not in the periodicity-based search in the survey. The reasons that this may arise is: 1) A pulsar has a very high nulling
fraction, thus a weak Fourier strength; 2) A pulsar has a pulse energy distribution with a weak average but extended tail; or 3) The presence of radio interference has caused a regularly-emitting pulsar’s periodicity to experience a degradation of signal strength, or to be masked or passed over in the inspection process. Pulsars in the third category make up a minority (≤5%) of single pulse search results, and can generally be identified by excising interference from the discovery data or obtaining cleaner follow-up observations.

We can analytically approximate what level of nulling and modulated pulsars will lead pulsars in a survey to be considered RRATs. McLaughlin & Cordes (2003) derived the signal-to-noise ratio found for a pulsar with unimodally and bimodally-distributed flux in a periodicity search and single pulse search. Let us consider a pulsar with single pulses above the survey detection threshold, where the average signal-to-noise ratio of detected pulses is given by $\langle [S/N]_{SP} \rangle$. To be considered a RRAT, $[S/N]_{FT}$ must be less than the periodicity detection threshold, $m_{FT}$. Following from McLaughlin & Cordes, we derive:

$$NF > 1 - \frac{\eta}{\zeta} \cdot \frac{2m_{FT}}{\langle [S/N]_{SP} \rangle} \cdot \sqrt{\frac{P}{T_{obs}}},$$

where $NF$ is the pulsar nulling fraction, $T_{obs}$ gives the observation length, $P$ is the pulsar period, and $\eta$ and $\zeta$ are pulse-shape-dependent parameters of order ~1. Similarly, a non-nulling, modulated pulsar will be considered a RRAT if:

$$\frac{S_{\text{max}}}{S_{\text{avg}}} > \frac{\zeta}{\eta} \cdot \frac{[S/N]_{SP}^2}{2m_{FT}} \cdot \frac{T_{obs}}{P};$$

where $S_{\text{max}}$ is the maximum flux likely to be emitted over the observing interval (as given by the pulse energy distribution statistics), $S_{\text{avg}}$ is the modified average pulse intensity defined by McLaughlin & Cordes (2003), and $[S/N]_{SP}$ represents the signal-to-noise ratio of the brightest pulse detected in the single pulse search. What is immediately notable about these equations is that whether upon discovery a pulsar is called a “RRAT” is dependent on the pulsar’s rotational period, and also highly survey dependent, changing with survey observing length and assumed detection thresholds (see also Keane 2010).

2.2. Discerning RRAT types

Several methods exist to determine the underlying nature of RRATs. Perhaps the most effective of these is in pulse energy distribution analysis (e.g. as in Keane et al. 2010, Miller et al. in prep). This can uncover energy bimodality (implying a nulling pulsar) or reveal distributions in energy and time that are consistent with the lognormal or power-law distributions typically attributed to pulsars. Thus far, few analyses of such kind have been published, and so we cannot reliably assess the percentile breakdown of the underlying emission type of the ~70 currently-identified RRATs. However, the cursory studies of Burke-Spolaor & Bailes (2009) and deeper studies of Keane et al. (2010) have indicated that it is likely a large fraction of RRATs are in fact undergoing nulling (or, at least, are bimodally distributed with a low state below the detection thresholds).

3. The extreme nature of RRATs in the pulsar population

We now seek to quantify how excessive modulation and nulling are in RRATs when compared with the distribution of these phenomena in the general pulsar population.

3.1. Pulse-to-pulse modulation

Previous studies have indicated that pulse-to-pulse energy density variations are typically lognormally distributed (e.g. Cognard et al. 1996; Cairns et al. 2004), or follow a power-
law distribution (as with giant micropulses; Johnston & Romani 2002). Soon after the first report of RRATs, Weltevrede et al. (2006) revealed that PSR B0656+14 has an extremely extended lognormal tail (such that $S_{\text{max}}/S_{\text{avg}} \approx 450$); they noted that were the pulsar at a greater distance, it would have been detected as a RRAT (fulfilling Eq. 2.2 above). Recently, the first targeted measurements of single pulse energy distributions for a large pulsar sample were reported by Burke-Spolaor et al. (2012). Their analysis suggested that long-tailed pulsars like B0656+14 are uncommon, and that most pulsars appear to cluster around a relatively narrow range in lognormal shape parameters.

In Figure 1, we reproduce the distribution of phase-dependent $S_{\text{max}}/S_{\text{avg}}$ measured for that sample. Using Eq. 2.2 and $m_{\text{FT}} = 6$ we have marked, for various surveys, the limit above which a pulsar with $P = 1$ s and $[S/N]_{SP} = 6$ will be discovered as a RRAT†. This appears to suggest that while single pulse searches may certainly uncover extremely modulated pulsars, pulsars do not necessarily have to exhibit excessive modulation to be found as RRATs in a search, particularly for surveys of relatively short duration.

3.2. Pulse nulling

There are three variations of nulling activity that have been recognised:

- "Standard" nulling (e.g. Ritchings 1976; Wang et al. 2007), in which nulling fractions range from a few percent up to ~95%, and activity timescales range seconds to minutes.

- High-fraction nulling, i.e. as in some RRATs. Analysis of these objects indicates NFs upwards of 99%. In objects discovered as RRATs, the typical null timescale far exceeds that of the emitting timescale (see Fig. 2).

- Intermittent pulsars (Kramer et al. 2006; Camilo et al. 2012), which undergo nulling and emission cycles on timescales of weeks to years.

The activity timescales in both null and active states appear to follow characteristic spans for all of these variations, and some nulling appears quasi-periodic. The pulsation rate of most RRAT discoveries tend to be reproducible between observations, and they may also exhibit long-timescale quasi-periodicities (Palliyaguru et al. 2011).

This consistency allows a comparison of average emission/null cycle for the various manifestations of nulling. Such an analysis was performed by Burke-Spolaor et al. (2011), who found that the cycle times of Wang et al. (2007) nulling pulsars appear continuously

† Note that this comparison is most accurate for surveys with a $T_{\text{obs}}$ similar to that of the distribution's sample, 9 minutes; if the distribution were made from shorter/longer observations, we would expect the distribution to extend to lower/higher values, respectively.
Figure 2. Here we show time series for pulsars exhibiting a range of emission activity timescales (top to bottom: Vela, PSRs J1646–6831, J1647–36, J1226–32; archival data from Edwards et al. 2001, all panels are of equal duration). Each time series has been dedispersed using the pulsar dispersion measure reported by the online psrcat database (Manchester et al. 2005). The binary scale below each time series shows an estimated representation of the null/emission state. PSRs J1226–32 and J1647–36 were reported as RRATs by Burke-Spolaor & Bailes (2009). PSR J1647–36 exhibits clusters of ~5–10 pulses per activity cycle, while PSR J1226–32 emits singular pulses, perhaps signifying a typical emission timescale of less than the rotational period.

Distributed with those of RRATs (as we would expect given Eq. 2.1). The NF ≥ 95% pulsars were exclusively highlighted by RRATs, with the highest exceeding 99.99%. Intermittent pulsars yet remain isolated from short-duration null cycle pulsars. This perhaps marks two distinct populations, however the lack of current surveys’ sensitivity to intermediate-timescale null cycles indicates that perhaps there is yet an undiscovered population of pulsars undergoing such nulling. It is the nature of extreme nulling pulsars (NF > 95%) which most motivates continued observations of RRAT discoveries, and on which we focus the remainder of this manuscript.

4. Nulling pulsars and the issue of birthrates

It is not yet known what triggers nulling activity in pulsars, and whether there is some internal plasma/energy timescale intrinsic to the pulsar, or an external influence like asteroid bombardment (Shannon & Cordes 2008). We have previously noted the issue of matching neutron star birthrates with the occurrence rate of the CCSN thought to produce pulsars; in this discourse we may find circumstantial clues to how nulling phenomena relate to other pulsar populations.

Taking the original 11 RRATs to be nulling objects, McLaughlin et al. (2006) calculated the implied population of Galactic pulsars to be 2–4 × 10⁵, several times larger than the estimates for standard pulsars (Lorimer et al. 2006). The high-nulling-fraction population makes the largest contribution to the factor of 5–6 excess in neutron star birthrates, with
other contributions made by radio quiescent populations such as X-ray dim isolated neutron stars, magnetars, and central compact objects (Keane & Kramer 2008). While it is perhaps feasible that birthrate estimates have been grossly overestimated, the CCSN rate has been grossly underestimated, or there is a highly effective alternate source of pulsar production, a very plausible solution to the birthrate discrepancy can be found by drawing an evolutionary link between nulling behaviours and other neutron star varieties.

5. Extreme nulling pulsars: evolutionary clues from recent studies

5.1. Spin parameters of RRATs with high nulling fraction

It has long been debated as to whether nulling fraction correlates with any pulsar spin parameters, particularly with $P$, $\dot{P}$, or characteristic age ($\tau_c$), as might be the case if nulling is related to pulsar evolution. No definitive answer has yet been provided, particularly as nulling studies seem to disagree: Ritchings (1976) first reported a $\text{NF} \propto \tau_c^{-1}$ relationship, whereas Rankin (1986) reported no clear correlation between these two parameters. Biggs (1992) subsequently reported only a weak $\text{NF} - \tau_c$ anti-correlation, and that in fact a stronger anti-correlation exists between the NF and the magnetic/rotational alignment of the pulsar beam. Most recently, Wang et al. (2007) performed a dedicated study of nulling for pulsars in the Parkes Multibeam survey, again reporting a weak anti-correlation of age with NF, noting that there is a higher tendency for pulsars with a high NF ($\gtrsim 60\%$) to be older than 5 Myr.

Single pulse searches are intrinsically biased to discover nulling pulsars with longer periods (Eq. 2.1), so a separate analysis of only RRATs cannot wholly inform the above discourse. However, ongoing timing observations (McLaughlin et al. 2009; Keane et al. 2011) have shown that RRATs discoveries seem to support the Wang et al. observation (most reported solutions show $\tau_c > 5$ Myr). Strikingly, the bridge in $P - \dot{P}$ space between canonical pulsars and both magnetars and X-ray dim isolated neutron stars is preferentially highlighted by RRAT discoveries. This seems to give a cursory indication that extreme nulling pulsars may somehow link these populations.

5.2. PSR J1819–1458: tying extreme nulling and magnetars?

One of the original McLaughlin et al. (2006) discoveries, PSR J1819–1458, shows the strongest evidence for an evolutionary tie between neutron star populations. Its estimated surface magnetic field strength, $B_{\text{surf}} = 5 \times 10^{13}$ G, is the highest known among RRATs, and lies just below the lowest known magnetar $B_{\text{surf}}$ (McLaughlin et al. 2006). Dedicated monitoring and timing of this pulsar led Lyne et al. (2009) to report the occurrence of an “anomalous glitch” in the pulsar, where the post-glitch recovery led to a net decrease in $\dot{P}$, rather than the increase typically observed in glitching pulsars. The implication of repeated occurrence of such glitches is that PSR J1819–1458 would experience secular migration from magnetar-like spin parameters to those of standard radio pulsars. That PSR J1819–1458 is currently magnetar-like is also supported by the properties of its detection the X-ray and infrared wavebands (Reynolds et al. 2006; Rea et al. 2010).

Of course, PSR J1819–1458 is only one example of an extreme nulling pulsar, and we cannot presume it represents the entirety of this population. Ongoing studies will reveal whether other objects reflect similar behaviours. Thus far only a few RRATs have been targeted for detailed study; McLaughlin et al. (2009) have reported on six more of the original 11 RRATs, noting that no glitches have yet been observed in these pulsars. Rea et al. (2010) furthermore found no infrared detection in PSR J1317–5759, and Kaplan et al. (2009) put limits on X-rays from PSRs J0847–4316 and J1846–0257.

We can identify several points of future study that will advance our understanding
of RRATs. In particular, targeted differentiation of modulated/nulling RRATs, and the obtainment of timing solutions for these objects, will provide measured spin parameters, a large number of pulse detections, and precise positions for these objects. This will lead to NF studies that include extreme-nulling objects to search for correlations with other neutron star properties. Further detection of (or limits on) the presence of glitches in these objects will explore their spin evolution in comparison with canonical pulsars and other neutron star populations. Finally, obtaining precise RRAT positions will overcome issues of crowded high-energy fields, and may lead to further understanding of these objects through X-ray and other high-energy detection.

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Central compact objects and their magnetic fields

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Abstract. Central compact objects (CCOs) are neutron stars that are found near the center of supernova remnants, and their association with supernova remnants indicates these neutron stars are young ($\lesssim 10^4$ yr). Here we review the observational properties of CCOs and discuss implications, especially their inferred magnetic fields. X-ray timing and spectral measurements suggest CCOs have relatively weak surface magnetic fields ($\sim 10^{10} - 10^{11}$ G). We argue that, rather than being created with intrinsically weak fields, CCOs are born with strong fields and we are only seeing a weak surface field that is transitory and evolving. This could imply that CCOs are one manifestation in a unified picture of neutron stars.

Keywords. pulsars: general, stars: magnetic field, stars: neutron, supernova remnants

1. Introduction

There are a variety of manifestations/classifications of neutron stars. Here we discuss the class dubbed central compact objects (CCOs). CCOs are very loosely defined but are generally characterized by the following observed properties: (1) CCOs are associated with supernova remnants (SNRs) and are therefore young (with ages $< a few \times 10^4$ yr), (2) CCOs possess thermal X-ray flux that is relatively constant (with X-ray luminosity $L_X \sim 10^{33}$ ergs s$^{-1}$ and a spectrum that can be fit by blackbodies from small hot emitting areas), and (3) CCOs have no optical or radio counterpart or pulsar wind nebula (see De Luca 2008; Gotthelf & Halpern 2008, for observational review, including other CCOs not discussed here; see also Halpern & Gotthelf 2010).

Only three CCOs currently have a spin period $P$ measured (as well as a measurement or upper limit on the time derivative of spin period $\dot{P}$): PSR J0821$-$4300 in SNR Puppis A has $P = 0.112$ s and $P < 3.5 \times 10^{-16}$ s$^{-1}$ (Gotthelf et al. 2010), 1E 1207.4$-$5209 in SNR PKS 1209$-$51/52 (also known as G296.5+10.0) has two comparable timing solutions with $P = 0.424$ s and $\dot{P} = 2.13 \times 10^{-17}$ s$^{-1}$ or $1.26 \times 10^{-16}$ s$^{-1}$ (Halpern & Gotthelf 2011), and PSR J1852+0040 in SNR Kesteven 79 has $P = 0.105$ s and $\dot{P} = 8.68 \times 10^{-18}$ s$^{-1}$ (Halpern & Gotthelf 2010). We hereafter refer to these three CCOs as Puppis A, 1E 1207, and Kes 79, respectively, and only discuss them since we are primarily interested in their magnetic fields.

The spin period derivative values for CCOs are low compared to most radio pulsars (see Fig. 1). Assuming their current $\dot{P}$ is a historical maximum or constant (which may not necessarily be true; see, e.g., Muslimov & Page 1996; Geppert et al. 1999; Ho 2011; Ho & Andersson 2012; Pons et al. 2012), then (1) their current spin period is approximately their spin period at birth, (2) their characteristic age $\tau_c (= P/2\dot{P}) \gg$ true age, where the true age of Puppis A is $4450 \pm 750$ yr (Becker et al. 2012), 1E 1207 is 7 kyr with a factor of 3 uncertainty (Roger et al. 1988), and Kes 79 is $5.4 - 7.5$ kyr (Sun et al. 2004), (3) their X-ray luminosity cannot be powered by rotational energy loss since $L_X > \dot{E} = 4\pi^2 I P^2 / P^3$. 

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2. Magnetic field of CCOs

There are two primary methods for determining neutron star magnetic fields. The first involves timing observations, i.e., measuring neutron star spin period $P$ and period derivative $\dot{P}$. Assuming that the rotational energy of the pulsar decreases as a result of the emission of magnetic dipole radiation, the field at the magnetic equator $B_e$ can be inferred from $P$ and $\dot{P}$, i.e., $B_e = 3.2 \times 10^{19} \text{ G } (P \dot{P})^{1/2}$; note that numerical calculations of pulsar magnetospheres yields $B_e \approx 2.6 \times 10^{19} \text{ G } [PP/(1 + \sin^2 \alpha)]^{1/2}$, where $\alpha$ is the angle between the rotation and magnetic axes (Spitkovsky 2006). Using their measured values of $P$ and $\dot{P}$, CCOs have an inferred magnetic field $B \sim 10^{10} - 10^{11} \text{ G}$ (see next).

The second method involves spectral measurements, i.e., identifying features in the neutron star spectrum with particular magnetic processes. Puppis A has a possible emission line at 0.7–0.8 keV (Gotthelf & Halpern 2009; De Luca et al. 2012), and 1E 1207 has broad absorption lines at 0.7 and 1.4 keV (Sanwal et al. 2002; Bignami et al. 2003). If we assume that a spectral line at energy $E$ is due to electron cyclotron resonance, then the magnetic field is $B = 10^{11} \text{ G } (E/1.16 \text{ keV})(1 + z_g)$, where $1 + z_g = (1 - 2GM/c^2 R)^{-1/2}$ is the gravitational redshift for a neutron star of mass $M$ and radius $R$. The observed lines suggest that CCOs have $B \sim (7 - 9) \times 10^{10} \text{ G}$, in agreement with the fields inferred from timing measurements (spectral fits of another CCO, the 330-yr-old neutron star in SNR Cassiopeia A, suggest it has $B < 10^{11} \text{ G}$; Ho & Heinke 2009).
The magnetic field of CCOs are in contrast to the majority of neutron stars, which possess $B \approx 10^{12} - 10^{13}$ G, as can be seen from Fig. 1. Furthermore, from population synthesis studies, neutron star magnetic fields at birth follow a lognormal distribution with an average and width of $\mu$ and $\sigma$ of $\log B = 12.95 \pm 0.55$ in the case of no field decay (Faucher-Giguère & Kaspi 2006) and $\log B = 13.25 \pm 0.6$ when accounting for (model-dependent) field decay (Popov et al. 2010). The natural question is then one of creation versus evolution: Are CCOs born with weak fields or are CCOs born with strong fields but evolve in such a way that they appear to have weak fields at an age of $\lesssim 10^4$ yr?

Halpern et al. (2007) argue for the former and propose that CCOs are neutron stars that are born spinning slowly. Because of their slow rotation, the dynamo mechanism for magnetic field generation is ineffective, and as a result, CCOs possess weak fields ($< 10^{11}$ G). However, there appears to be several problems with this creation scenario. First, CCOs do not spin particularly slowly, as illustrated in Fig. 1; this is supported by population synthesis work, which yields a normal distribution for neutron star spin periods at birth with an average and width of $P = 0.30 \pm 0.15$ s in the case of no field decay (Faucher-Giguère & Kaspi 2006) and $P = 0.25 \pm 0.1$ s when accounting for field decay (Popov et al. 2010). Second, a birth field $< 10^{11}$ G would require CCOs to be $\gtrsim 4\sigma$ from the peak of the neutron star distribution, and therefore there should be very few of them relative to the normal pulsar population. But this is counter to their observed numbers. For example, De Luca (2008) finds six CCOs, compared to fourteen radio pulsars, in all known SNRs within 5 kpc (see also Halpern & Gotthelf 2010), and Kaspi (2010) estimates a CCO birthrate of $\sim 0.0004$ yr$^{-1}$ (since all known CCOs are $\lesssim 7$ kyr old) and $\gtrsim 10^6$ CCOs in the Galaxy (comparable to the number of strong magnetic field neutron stars). We consider now an alternative to the creation scenario, namely evolution.

3. Modeling magnetic field evolution

In the evolution scenario, CCOs are born with strong fields ($B > 10^{12}$ G), and these fields either decayed rapidly to their current strengths or were buried by an early episode of accretion and are emerging or emerged recently. Magnetic field diffusion and decay conventionally occurs on the Ohmic timescale $\tau_{\text{Ohm}} = 4\pi \sigma c L^2/e^2 \sim 4 \times 10^5$ yr $(\sigma c/10^{24}$ s$^{-1})(L/1$ km)$^2$, where $\sigma c$ is the electrical conductivity, $L$ is the length-scale over which decay occurs, and 1 km is the approximate size of the stellar crust (see Goldreich & Reisenegger 1992). Thus fast decay from $\sim 10^{13}$ G to $\sim 10^{11}$ G could only have occurred in CCOs if the field is confined to very shallow layers in the star (Ho 2011).

In Ho (2011), we compare the observed properties of Puppis A, 1E 1207, and Kes 79 to our calculations of the evolution of a buried magnetic field. We assume the field is buried deep beneath the surface (Romani 1990), perhaps by a post-supernova episode of hypercritical accretion (Chevalier 1989; Geppert et al. 1999; Bernal et al. 2010). These fields then diffuse to the surface on the timescale of $10^2 - 10^4$ yr, so that only now do we see a surface field $\sim 10^{10} - 10^{11}$ G. We solve the induction equation, $\partial B/\partial t = -\nabla \times (\mu_0 c^2/(4\pi \sigma) \nabla \times B) \sim B/\tau_{\text{Ohm}}$, in one spatial dimension (see also Muslimov & Page 1995; Geppert et al. 1999, for non-CCOs), while Viganò & Pons (2012) perform two-dimensional simulations (and thus are able to account for Hall drift) of burial and emergence of magnetic fields in CCOs. Fig. 1 shows examples of how evolution of an initially submerged magnetic field could change $P$ and $\dot{P}$ for the CCOs. For a field that is confined to the crust, we also find a unique relationship between accreted mass $\Delta M$ and birth magnetic field, with a minimum log $B \approx 11.4 - 11.7$. We find that measuring $dB/dt$ or the pulsar braking index would allow a determination of $\Delta M$, $B$, and the field configuration, e.g., the field is purely in the crust if $dB/dt < 0$, while $\Delta M$ is large and the
field is buried deep if $dB/dt > 0$ and large. We note that the (candidate) emission line seen in Puppis A has decreased in energy by 10% in 8.5 yr (De Luca et al. 2012); if this is associated with a decaying magnetic field, then a purely crustal field is implied, although the decay may be too rapid. We also note that optical/IR observations of 1E 1207 place a limit of $\Delta M < 10^{-6} M_\odot$ on the initial mass of a debris disk (De Luca et al. 2011).

4. Modeling the magnetized atmosphere spectrum of CCOs

In addition to advancements in understanding CCO timing properties, progress has been made in modeling their spectra. The observed thermal radiation originates in a thin atmospheric layer (with scale height $\sim 1$ cm) that covers the stellar surface. The properties of the atmosphere, such as the magnetic field, chemical composition, and radiative opacities, directly determine the characteristics of the observed spectrum (see, e.g., Zavlin 2009, for review). Very importantly, magnetic fields $B > e^3 m_e^2 c/\hbar^3 = 2.35 \times 10^9$ G significantly increase the binding energy of atoms, molecules, and other bound states, and their abundances can be appreciable in the atmospheres of neutron stars (see Lai 2001, for review). Furthermore, when $B \sim 10^{11}$ G ($T/a \sim 10^6$ K), models of atmosphere spectra must properly account for quantum and thermal effects in the Gaunt factor or Coulomb logarithm, which give rise to strong cyclotron harmonics in the opacity (Pavlov & Panov 1976; Pavlov et al. 1980; Potekhin 2010; Suleimanov et al. 2010, 2012). These effects are needed in order to interpret the strong absorption lines seen in 1E 1207 as the result of electron cyclotron resonance in an atmosphere with $B \sim 7 \times 10^{10}$ G, where the observed 0.7 and 1.4 keV lines are the fundamental and first harmonic, respectively (see, e.g., Ho & Mori 2008, for alternative interpretations).

We construct fully ionized hydrogen atmosphere models using the method described in Ho & Lai (2001) and using Potekhin & Chabrier (2003) to calculate Gaunt factors and Suleimanov et al. (2012) to account for thermal effects. Examples of the resulting spectra are shown in Fig. 2. We note that these weak field ($B = 10^{10} - 10^{11}$ G) neutron star atmosphere spectra will be implemented in XSPEC under NSMAX (Ho et al. 2008), while partially ionized hydrogen models will be the subject of future work. The spectra shown in Fig. 2 only describe emission from either a local patch of the stellar surface with a particular effective temperature and magnetic field or a star with a uniform temperature and radial magnetic field of uniform strength. By taking into account surface magnetic field and temperature distributions, we can construct more physical models of emission from neutron stars (see Ho 2007, for details). As an illustration, Fig. 3 shows the phase-resolved model spectra, pulse profile, and pulse fraction. We assume here that
1 + \( z_g \) = 1.235 and angles between rotation and magnetic axes and between rotation axis and observer are 5\(^\circ\) and 25\(^\circ\). The hot spot covers magnetic colatitudes 0\(^\circ\) to 30\(^\circ\) and has effective temperature \( T_{\text{eff}} = 2 \times 10^6 \) G and magnetic field \( B = 7 \times 10^{10} \) G that is oriented parallel to the surface normal. The bottom panel shows the pulse fraction in different energy bands that is measured for 1E 1207 (De Luca et al. 2004); what is particularly noteworthy is that the pulse fraction is larger at the spectral lines, and accounting for thermal effects in the model appears to be necessary to achieve these higher pulse fractions (see also Suleimanov et al. 2012).

5. Discussion

From timing and spectral studies, CCOs appear to have relatively weak surface magnetic fields (\( B \approx 10^{10} - 10^{11} \) G). The question arises as to whether CCOs are born with inherently weak magnetic fields (creation scenario) or they are born with much stronger fields but these fields were buried and are evolving (evolution scenario). The creation explanation is simple, but as discussed in Sec. 2, there are problems. There are also problems with the evolution scenario (see, e.g., Halpern & Gotthelf 2010). Nevertheless, evolution of magnetic fields seems natural, and there is evidence in favor of buried magnetic fields in CCOs. For example, Shabaltas & Lai (2012) construct models with strong toroidal fields (\( B > 10^{14} \) G) in the crust to explain the high pulse fraction of Kes 79 (64 ± 2%; Halpern & Gotthelf 2010). Also Gotthelf et al. (2010) argue that a strong tangential field in the crust can explain the small hot spots seen on Puppis A, and this is confirmed qualitatively with magneto-thermal simulations by Viganò & Pons (2012).

If CCOs have buried magnetic fields, then this sub-surface field is likely to be \( \gtrsim 10^{12} \) G. If burial is shallow, then the surface field is currently decaying. If burial is deep, then the surface field is growing rapidly and could lead to a rapid change in spin parameters. We see from Fig. 1 that CCOs reside in a relatively underpopulated region of \( P - \dot{P} \) parameter space (see also Halpern & Gotthelf 2010; Kaspi 2010). Rapid spin evolution could mean that CCOs are moving out of this region quickly and joining the majority of the pulsar population at longer spin periods, higher \( \dot{P} \), and stronger observed magnetic fields. Thus magnetic field evolution could facilitate the unification of CCOs with other classes of neutron stars (see Kaspi 2010; Popov et al. 2010; Ho 2012).

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Discoveries of Rotating Radio Transients in the 350 MHz Green Bank Telescope Drift-scan Survey

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Abstract. Rotating Radio Transients (RRATs) are a class of pulsars characterized by sporadic bursts of radio emission, which make them difficult to detect in typical periodicity-based pulsar searches. Using newly developed post-processing techniques for automatically identifying single bright astrophysical pulses, such as those emitted from RRATs, we have discovered approximately 30 new RRAT candidates in data from the Green Bank Telescope 350 MHz drift-scan survey. A total of 6 of these have already been confirmed and the remainder look extremely promising. Here we describe these techniques and present the most recent results on these new RRAT candidates.

Keywords. stars: neutron, pulsars: general, surveys

1. Introduction

Rotating Radio Transients (RRATs) were first discovered by McLaughlin \textit{et al.} (2006) and are characterized by occasional single radio pulses, with no underlying periodicity easily detected, in contrast to typical rotation-powered pulsars. The discovery of RRATs was surprising and important as it revealed a class of neutron stars that had previously been missed by pulsar surveys, thereby suggesting a potentially enormous increase in the inferred neutron-star birthrate. Moreover the discovery raised the issue of why some neutron stars show such sporadic emission, whereas others are ‘on’ continuously. RRATs may exhibit up to $\sim 1000$ periods of separation between detected pulses, and as such are not detected in periodicity searches. Furthermore, observational biases against detecting RRATs suggest that these sources represent a significant fraction of radio-active Galactic neutron stars, yet the current known population is very small. Today $\sim 70$ RRATs are known\textsuperscript{†} however the vast majority do not yet have their basic properties measured. Those RRATs whose properties have been measured tend to have longer periods and are mostly seen to lie between the regular pulsars and the magnetars, as shown in the $P-\dot{P}$ diagram in Figure 1. This may suggest an evolutionary link between RRATs and other pulsar classes, but with such a small known RRAT population, it is difficult to draw conclusions regarding their place within the global pulsar population.

Since the initial discovery of the first 11 RRATs, there has been a major paradigm shift in radio pulsar searches. Single-pulse searches are now routine and a large number of new RRAT discoveries are being made (e.g. Keane \textit{et al.} 2010; 2011). On the other hand, a lot of human involvement is required in examining the output of single-pulse searches in order to look for RRAT-like patterns. This, along with the already present

\textsuperscript{†} See the “RRATalog” at http://www.as.wvu.edu/~pulsar/rratalog/ for a list.
Figure 1. $P - \dot{P}$ diagram for all known neutron stars outside of globular clusters. The 18 RRATs with measured $\dot{P}$ are indicated by triangles, and dots represent other neutron stars. Lines of constant magnetic field are solid and lines of constant characteristic age are dashed. As can be seen, these 18 RRATs tend to have longer periods and larger magnetic fields than the bulk of long-period pulsars.

biases against finding RRATs, makes expanding and studying the RRAT population a difficult task. Hence, it is imperative to make automated RRAT searches a routine part of radio pulsar searching.

We have developed new post-processing techniques for automatically identifying single bright astrophysical pulses, such as those emitted from RRATs. In implementing this search algorithm on data from the Green Bank Telescope 350 MHz Drift-scan Survey, we have discovered 33 new RRAT candidates, of which 6 have already been confirmed. Here we describe these techniques and present our discoveries.

2. The Green Bank Telescope 350 MHz Drift-scan Survey

We have searched for RRATs in data from the Green Bank Telescope (GBT) 350 MHz Drift-scan Survey. This survey was conducted over the summer of 2007, while the azimuth track of the GBT was undergoing repairs, and thus the telescope was stationary at several fixed elevations, collecting data as the sky drifted over it. The data were analyzed in 140-s sections, corresponding roughly to the time it takes a point on the sky to pass through the full width half maximum of the telescope beam. This survey produced 134 TB of data, covering over 10,000 square degrees of the sky, and has yielded 34 pulsars thus far. For more information on this survey, see Boyles et al. (2012) and Lynch et al. (2012).

These data were then processed using the PRESTO software suite (Ransom 2001), which included radio frequency interference (RFI) excision, de-dispersion, searches for periodic signals in the Fourier domain, and single-pulse searches. In single-pulse searches, signals in the de-dispersed time series that deviate from the mean significantly are identified, and information such as signal-to-noise, time, dispersion measure (DM), and pulse width is recorded. Diagnostic “single-pulse plots” summarizing this information are then produced for each beam and saved for human inspection. In this survey, the data were divided into 30,000 140-s “pointings”, producing 120,000 such diagnostic plots (4 plots per pointing, each plot spanning a different DM range) that then required visual examination. This is a tedious, time-consuming task, and can thus be a bottleneck in discovering single-pulse sources.
3. RRAT search algorithm

We have developed an automated search algorithm in order to identify RRAT candidates in the output of single-pulse searches described above, eliminating the need for manual inspection of each diagnostic plot produced. Our algorithm is based on the following concepts:

(a) A bright signal will be detected over a range of DMs, with the strongest detection at the optimal DM and weaker detections above and below this DM.

(b) Since signals are strongest at the optimal DM, we expect that signals of terrestrial origin (namely RFI) will peak at a DM of 0. We can thus classify any signals that peak at DM~0 as not astrophysical and reject them.

Concept (a) means that a given pulse, whether astrophysical or not, will be associated with many statistically significant “single-pulse events” that will be found in the single-pulse search. These events will be spread over a small range of DMs, and will occur at approximately the same time. The first step in our algorithm is thus to group events that belong to the same pulse by checking whether they satisfy this criterion, that is, lie within some small window of DM and time. Once the single-pulse events in a beam have been divided into groups, we examine each group’s collective properties in order to decide whether it behaves like an astrophysical pulse, and rate it based on these results.

The first test we employ is group size. If a group has too few events, we classify it as noise. The following test examines signal-to-noise vs. DM behaviour. From concept (b), we expect that a group of events that is due to an RFI signal will have a peak signal-to-noise at DM~0. Thus, any groups that satisfy this criterion are classified as RFI. Finally, we again make use of concept (a) by looking for groups that have peak signal-to-noise at some given (non-zero) DM, which then decreases above and below that given DM. These groups are classified as likely astrophysical pulses, and depending on the peak signal-to-noise attained, are classified as “likely” to “very likely” pulses.

Once the beams have all undergone this search algorithm, those that have been flagged as having “very likely” pulses are visually examined. For those beams that indeed look like astrophysical sources, we then generate “waterfall plots”, which are frequency vs. time plots that show arrival times of the signal in different frequency bins. Since astrophysical signals experience a frequency-dependent dispersive delay while propagating through the interstellar medium, we use these waterfall plots as a final means of testing the astrophysical nature of a signal, before deciding whether it is a candidate worthy of follow-up.

4. Results

We have processed all 30,000 pointings of the GBT Drift-scan Survey with the search algorithm described above, resulting in a total of 33 RRAT candidates. Of the 7 candidates that have been followed up, 6 have been confirmed. The remaining sources look extremely promising, based on their strong single-pulse detections, as well as dispersive behaviour shown in waterfall plots. It should be noted that, remarkably, the number of RRAT candidates found is comparable to that of regular pulsars (34) found in the Drift-scan Survey. Figure 2 shows an example discovery and confirmation plot of one of the new RRAT sources. The strength of the algorithm is illustrated in these plots: the pulses in the discovery observation may easily be confused with RFI when examined by eye, and this beam would have potentially been dismissed if it were only examined visually. The algorithm, however, successfully distinguished between the astrophysical pulses and the RFI in this beam, and correctly identified this source as an RRAT candidate.
Figure 2. Discovery (left) and confirmation (right) single-pulse plots for newly discovered RRAT J1537+2350. The lower panel shows single-pulse events at the DM and time for which they were detected, with dot size proportional to signal-to-noise ratio. Notice, on the left, 5 pulses at $\text{DM} \sim 15 \text{ pc cm}^{-3}$, starting at $t \sim 37 \text{ s}$, and various RFI spikes throughout. On the right, many strong pulses are seen, again at $\text{DM} \sim 15 \text{ pc cm}^{-3}$. The top right panels of each diagram demonstrate the signal-to-noise vs. DM behaviour expected for an astrophysical pulse, as described in Section 3.

5. Future work

We hope to begin timing the confirmed RRAT sources soon, allowing us to measure their basic parameters and place them on the $P - \dot{P}$ diagram. We will also follow up the remaining candidates, and begin timing observations of those that are confirmed.

We are also working on making improvements to the search algorithm that will allow us to identify weaker pulses in data, as well as make the algorithm more robust to RFI in order to reduce the number of false positives. Finally, since this code is not specific to the Drift-scan Survey it may be applied to other pulsar surveys. Indeed, in the coming weeks it will be implemented in the ongoing Green Bank North Celestial Cap Survey. Applying the search algorithm to this extensive sky survey promises to yield many more RRAT sources, since this survey will have improved sensitivity and will cover an area far larger than that of the GBT Drift-scan survey.

We hope that with this new automated search algorithm, the known RRAT population will quickly grow, allowing us to study more of these fascinating objects and find their place within the global pulsar population.

References

Pulsar searches in nearby dwarf spheroidal galaxies

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Abstract. We have been undertaking a comprehensive survey for pulsars and fast radio transients in the dwarf spheroidal satellite galaxies of the Milky Way using the Green Bank Radio Telescope operating at a central frequency of 350 MHz. Our search pipeline allows the detection of periodical signals and single dispersed pulses and it is optimized to search for millisecond radio pulsars. Here we present preliminary results of the searches we have conducted in the Ursa Minoris, Draco and Leo I dwarf spheroidal satellite galaxies. Our searches have revealed no periodic signals but a few unconfirmed millisecond single pulses at various dispersion measures, possibly related to neutron stars. Detecting neutron stars in these systems can potentially help to test the existence of haloes of dark matter surrounding these systems as predicted by Dehnen & King (2006).

Keywords. galaxies: dwarf spheroidals, –stars: neutron, –pulsars: general, searches, individual pulses.

1. Introduction

Searches for any manifestation of neutron stars at radio wavelengths such as pulsars, in nearby galaxies can help us to probe insightful information about the stellar content, dynamics and about the intergalactic medium surrounding them. Until recently, only a few of the satellites of our Milky Way have been searched for pulsars and these searches have been concentrated in the Magellanic Clouds resulting in the discovery of a few tens of new pulsars (McCulloch et al. 1983, Manchester et al. 2006 and references therein). This high detection rate is mainly because of the large star formation rates of these clouds. Searches for pulsars in galaxies other than the Magellanic Clouds have been hampered by the enormous distances at which these objects lie, and by the limitations in the dwell times of the observations which constrain the S/N at which these objects can be detected. Some previous attempts of detecting pulsars in these objects are the observations made in the Fornax dwarf spheroidal by McLaughlin & Cordes (2003) which resulted in no detections.

Despite the fact that dwarf spheroidal galaxies (hereafter dSph) have had almost no recent episodes of stellar formation and that these objects display low metallicities, we have two main motivations for searching pulsars in these objects. The first one is the discovery of 5 low–mass X–ray binaries (LMXBs), in the Sculptor Spheroidal Dwarf Galaxy (Maccarone et al. 2005) which proves that this kind of object can exist in an old stellar population, an environment where star formation and stellar encounters are low. The fact that the distances and stellar populations of the dwarf companion galaxies
have been well established makes these objects ideal places for the search of rare classes of binary stars and their descendants such as millisecond pulsars (MSPs). Our second motivation is that finding neutron stars in the dSph galaxies, can potentially help us to investigate the dark matter component of these galaxies as we explain. When neutron stars are formed during the Type II supernova explosion, they get a typically kick velocity that varies between 20–200 km s\(^{-1}\) (Podsiadlowski et al. 2005) which exceeds the velocity dispersion of the stellar components in the dSph of \(\sim 6\) km s\(^{-1}\). Dehnen & King (2006) proved that if these galaxies have haloes of dark matter, there should be also haloes of neutron stars at highly eccentric orbits, composed by either Low Mass X–ray Binaries (LMXBs), MSPs which are direct descendants from LMXBs and perhaps some old and still active radio pulsar. This prediction can be tested implementing a systematic search for any manifestation of pulsars in these galaxies at radio wavelengths.

Many factors may hemper these searches such as the enormous distances at which the dSph are located, the very low numbers of MSPs within them, the beaming effects and low luminosities. However to increase the chance of detecting these pulsars and get an idea of their spatial distribution within these galaxies with the current facilities, one could observe many (if not all) the dSph satellites of our Galaxy. We have initiated a campaign to observe some of these galaxies and here we present our preliminary results.

2. Observations and data reduction

A summary of the observations of the dSph galaxies reported here is shown in Table 1. All these observations were made using the Green Bank Radio Telescope (GBT) operating at a central frequency of 350 MHz and using the GUPPI pulsar card. At this frequency the beam size of the GBT is about 0.6\(^\circ\), much larger than the angular size of the main bulge of our targets. In every observation we have sampled the data at 81.92 \(\mu\)s using a bandwidth \(\Delta f = 100\) MHz across 4096 frequency channels. Our observations were reduced using the PRESTO package (Ransom et al. 2002) applying periodicity searches optimized for detecting MSPs. We have also implemented single pulse searches in our reduction pipeline. For the reduction we have used the cluster ATOCATL located at the Institute of Astronomy of the National Autonomous University of Mexico.

Our reduction process starts by finding radio frequency interference (RFI) in our data and removing frequencies related to RFI. Later we prepare timeseries for all the trial dispersion measures (DMs) in which we perform the searches. The trial DMs are spaced adequately in order to maximize the sensitivity of the data to millisecond pulsars. We have produced a total of 12468 trial DM timeseries with step sizes of 0.05, 0.1 and 0.3 pc cm\(^{-3}\), each corresponding to the first and second DM diagonal located at DM= 346.50 and DM= 600 pc cm\(^{-3}\) (the point where the dispersion delay across a frequency channel is equal to twice the sampling time). We now explain the basics of our searching methods. A detailed explanation of our pipeline analysis and its sensitivity will be published elsewhere. For the periodicity searches we have used an FFT algorithm that searches for all the relevant spectral features which are stored and used later to search for accelerations summing up to 8 harmonics. At this point we search the data in segments of 10, 20 minutes to be sensitive to systems with short orbital periods. For systems consisting of weak/distant pulsars we also analyzed the data using segments of 60 and 120 min.

For the single pulse searches we have used the routine SINGLE PULSE SEARCH of PRESTO. This routine attempts to find single pulses by applying a match filter to the data with a series of boxcar functions of different widths. For our searches we add 1,2,3,4,6,9,14,
Table 1. GBT observations of the dSph galaxies satellites presented here

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>RA (J2000.0) (h.m.s.)</th>
<th>DEC (J2000.0) (d.m.s.)</th>
<th>ℓ (deg)</th>
<th>b (deg)</th>
<th>N_p</th>
<th>D (deg)</th>
<th>Total Dwell (kpc)</th>
<th>Time (s)</th>
</tr>
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<td>Ursa Minoris</td>
<td>15:09:08.04</td>
<td>+67:13:21.36</td>
<td>104.9662</td>
<td>44.8012</td>
<td>1</td>
<td>60</td>
<td>17610</td>
<td></td>
</tr>
<tr>
<td>Draco</td>
<td>17:20:12.12</td>
<td>+57:54:55.80</td>
<td>86.3681</td>
<td>34.7226</td>
<td>2</td>
<td>80</td>
<td>15670</td>
<td></td>
</tr>
<tr>
<td>Leo I</td>
<td>10:08:27.00</td>
<td>+12:18:27.36</td>
<td>225.9816</td>
<td>49.1090</td>
<td>5</td>
<td>250</td>
<td>60000</td>
<td></td>
</tr>
</tbody>
</table>

20, 30, 45, 70 and 100 bins of data in order to be sensitive to pulses of different width (W). This routine filters duplicate candidates and records only the most significant ones (S/N > 5), this threshold is chosen following the statistics for single pulses explained in Cordes & McLaughlin (2003). We have excised from the timeseries all the times where RFI was identified. All the relevant pulses that match this criteria are recorded and inspected later.

3. Preliminary results and discussion

We have completed the periodicity searches and single pulse analysis of all the galaxies listed in Table 1. These observations are part of a larger data set of dwarf spheroidal galaxies that is being reduced now and that will be published elsewhere. Our searches have revealed so far none MSPs or normal pulsars and a few single pulses. Three of the best detections were recorded in are the direction of the Ursa Minoris dSph and are shown in Figure 1. These unconfirmed sources may be of extragalactic origin (i.e. outside our Galaxy and not in the Ursa Minor dSph) or some unknown form of interference. The argument in favour of their extragalactic origin is the high DM they show. Given the large column density required, compared with the observational constraints on the column density in the Ursa Minor galaxy (Gallagher et al. 2003), in the future we plan to take additional care to ensure that these pulses are real astrophysical sources by analyzing the spectrum of the individual single pulses. We show here preliminary results, a more detailed analysis of our results will be presented elsewhere.

Figure 1. Three examples of bright pulses detected in the Ursa Minoris dSph galaxy. The high DM of these bursts (DM > 200 pc cm$^{-3}$) locates them well outside our Galaxy. In the left we show two pulses detected with a S/N > 7.0 while in the right one detected with a S/N > 8. These pulses were not detected in other observations.
4. Conclusions and future work

We have presented some preliminary results of a work in progress. We have shown here that searches for pulsars in dSph galaxies can offer us a unique possibility to probe the intergalactic medium (by constraining the electronic content of it) and the stellar content of these galaxies by confirming the existence of MSPs or normal pulsars. If any of these objects is detected and we locate it, we could establish if they form haloes and confirm the predictions made by Dehnen & King (2006). The fact that we sample the radio sky for long periods also increases our chances of detecting rare and perhaps new transient sources such as the so–called Lorimer burst (Lorimer et al. 2007). For the future we aim to:

- Finish the reduction of more data taken from other dSph that will be collected at the GBT, as well as the reduction of archival data taken with the GBT and the Arecibo radio telescopes of a few other dSph galaxies.
- Develop synthetic models to describe the pulsar population of the dSph galaxies in order to predict the number of detectable neutron stars in these systems. We aim to be able to establish the probability of successful detections of MSPs and normal pulsars with the current facilities such as the Parkes, GBT and the Arecibo radio telescopes.
- Investigate these objects with larger instruments. The outstanding sensitivity that LOFAR will have (see Stappers et al, 2011), and the proposed Square Kilometre Array (SKA) may confirm the existence of MSPs in these dSph galaxies. With appropriate timing and sufficient observations it may be possible to establish their spatial distribution and perhaps the dynamics of these systems which in turn can be used to constrain the shape and distribution of dark matter in these objects.

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References

Abstract. Radiation of most of the known pulsars is powered by the loss of their rotational energy and angular momentum. Thanks to the Chandra and XMM-Newton observatories, X-ray emission has been detected from over 100 rotation-powered pulsars in the last 12 years. I will overview the current results of X-ray observations of rotation-powered pulsars, including the evolution of the X-ray properties, thermal and magnetospheric components of X-ray emission, and connection between the X-ray emission and emission at other wavelengths.
The decaying magnetic field of magnetars: evidence and inference

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Abstract. Magnetic field decay in neutron stars has been a long debated subject, since the early realization that radio pulsars were likely spinning neutron stars endowed with a 1E12 G magnetic dipole. This problem has however eluded all attempts of solution so far, mostly due to the scarcity of observational indications. Here I discuss the observational evidence for decay of the dipole magnetic field in magnetar candidates (Soft Gamma Repeaters and Anomalous X-ray Pulsars) and present a quantitative study of its main properties. I show that the decaying dipole does not have enough energy to power the persistent X-ray emission of magnetars. The latter must thus directly reveal the decay of an additional, stronger field component, presumably hidden in the interior of these neutron stars. Using existing models it is possible to characterize the salient properties of this internal field component and their implications for magnetar astrophysics. Finally, I sketch preliminary considerations on evolutionary links between magnetars and other classes of neutron stars with strong dipole field that do not show magnetar-like activity.
The first radio-quiet millisecond pulsar?

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Abstract. The Fermi-LAT source 2FGL J2339.6-0532 is likely to host a millisecond pulsar in a 'black-widow' system. Strong indications of its nature come from gamma rays and particularly from optical and X-ray observations. However, no pulsations have been found so far neither in radio nor in gamma rays, despite deep searches. I will present here our efforts to find pulsations in Fermi-LAT data. I will describe the uncertainties in the orbital and spin parameters of the source, broadly covered in our search. I will prove the robustness of our technique on other similar systems, and through simulations. I will present the results of our search: the most likely candidates and the further constraints on the parameters of the putative pulsar. Finally, I will discuss the implications of our results and the prospects to find pulsations in this and other similar systems in the future.
Session 5

Binary Pulsars
Binary pulsar evolution: unveiled links and new species
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Abstract. In the last years a series of blind and/or targeted pulsar searches led to almost triple the number of known binary pulsars in the galactic field with respect to a decade ago. The focus will be on few outliers, which are emerging from the average properties of the enlarged binary pulsar population. Some of them may represent the long sought missing links between two kinds of neutron star binaries, while others could represent the stereotype of new groups of binaries, resulting from an evolutionary path which is more exotic than those considered until recently. In particular, a new class of binaries, which can be dubbed Ultra Low Mass Binary Pulsars (ULMBPs), is emerging from recent data.

Keywords. stars: neutron, pulsars: general, stars: white dwarfs, binaries: general, binaries: close, binaries: eclipsing

1. Introduction

The focus of this contribution is on the so-called recycled pulsars (see e.g. Alpar et al. (1982), Radhakrishnan & Srinivasan 1982), i.e. neutron stars which are supposed to have experienced at least one phase of accretion of mass and angular momentum from a companion star, during which the system appeared as an X–ray binary. This phase should lead to a significant acceleration of the spin rate $P$ of the star, accompanied by a decay (the physical origin of which is still subject of discussion, e.g. Konar 2010) of the surface magnetic field $B_s$ (Bisnovatyi-Kogan & Komberg 1974). At the end of the process, the value of $P$ and $B_s$ are suitable for the neutron star to shine as a radio pulsar, located in the lower left part of the $P$–$B_s$ diagram, with $P \leq 100$ ms and $10^7 \leq B_s \leq 10^{10}$ Gauss.

During the last years, many new effective pulsar search experiments (see later) have favored a flourishing in the discoveries of this class of pulsars in the Galactic field. That is expected to trigger a new Golden Era for the studies of the evolution of the binaries including a neutron star. That already happened in the past decade for the class of the high mass binary pulsars (HMBPs) and for that of the binary pulsars in the globular clusters, with a wealth of studies stimulated by the doubling of the catalogued double neutron star binaries (including the first and still unique double pulsar) and by the doubling of the known pulsars in the clusters.

In the framework of the recycling scenario, HMBPs are expected to evolve from a neutron star with a massive companion ($\gtrsim 6 – 8 M_\odot$), the rapid evolution of which leads to a relatively short X–ray phase and then only to a mild spin-up ($P$ of order tens of milliseconds, hence the name of mildly recycled pulsars) and a moderate magnetic field decay, $B_s \gtrsim 10^9$ Gauss. If the binary survives the (second) supernova, we are typically left with a double neutron star binary in an eccentric orbit (see e.g. van den Heuvel & de Loore 1973, Bhattacharya & van den Heuvel(1991)). The high stellar density in the globular cluster cores - where most of the pulsars are expected to reside due to mass segregation - strongly enhances the probability that the binary evolution is affected by
the internal dynamics of the cluster, as a result of 3 (or 4) body encounters. Many works have been devoted to study these intriguing physical conditions (see Freire’s contribution in this volume), but obviously they are not ideal for tracing the evolution of a binary due to purely internal effects, as is the case for the binary pulsars in the Galactic field.

The main focus here will be on objects belonging to the classes of the intermediate mass (IMBPs) and low mass binary pulsars (LMBPs). After an update on the demography of the recycled pulsars population follows a summary of some recent observational results about the evolution of those two families of systems, also listing the cases of few binaries which, in my personal opinion, represent the highlights for the current research in this field. In view of the space limitation, in many cases the reader will be forwarded to other contributions in this volume for a detailed presentation of the various models/sources.

2. Demography

Figure 1 shows the occurrence, during the last 2-3 years, of a steep increase in the number of catalogued recycled pulsars. In particular the overall count of recycled pulsars has almost doubled with respect to the year 2009 (left panel), nowadays accounting for over 10% of the whole known population of ∼2100 pulsars (right panel). This was due to the combination of two factors. (i) The possibility of performing targeted searches in the radio bands of properly selected unidentified Fermi γ-ray sources. These led to a (somewhat unexpected) very high efficiency in discovering recycled pulsars (43 at the time of writing) in the proximity of the Sun, i.e. typically within 1−2 kpc (see e.g. Guillemot et al., this volume). (ii) The launch of a series of new pulsar search experiments designed to have better spectral and time resolution than any previous large scale survey (see e.g. Keith et al., Lazarus et al. and Lynch et al. in this volume). As a whole, these searches have added 60 new objects to the catalog (as of August 2012), a significant fraction of them showing a high dispersion measure and thus located in regions of the Galaxy where the population of recycled pulsars had been poorly sampled by previous experiments. In fact, in recent surveys the fraction of new recycled pulsars ranges between 15% and 25%, well beyond the typical 5 – 10% values of past blind searches.

![Figure 1. Chronological trends (left panel) in the number of catalogued recycled pulsars (solid line) and (right panel) in the ratio between known recycled pulsars and the total population of pulsars. The trends for the subgroups of the binaries, the isolated and the not yet classified (N.C.) recycled pulsars are also reported. Pulsars belonging to the globular clusters have been excluded. Data are taken from the ATNF pulsar catalog (Manchester et al. 2005) on August 2012 (http://www.atnf.csiro.au/research/pulsar/psrcat) as well as from some private communications (thanks in particular to Lorimer and to Burgay) for the still unpublished objects.](image-url)
3. IMBPs and LMBPs

A recent attempt to summarize most of the current knowledge about the evolution leading to the formation of IMBPs and LMBPs has been provided by Tauris (2011) and Tauris, Langer & Kramer 2012 (see also Tauris’ contribution, this volume). In these systems the initial companion mass is \( \lesssim 1 - 2 \, M_\odot \) for the LMBPs and around 3-6 \( M_\odot \) for the IMBPs (although an initial companion mass up to \( \sim 9 \, M_\odot \) can be invoked for IMBP binaries which evolved from a very large orbit), implying longer stages of accretion than for HMBPs. That can lead, mostly for the LMBPs, to re-acceleration of the neutron star to millisecond periods (\textit{fully recycled} pulsars), while the surface magnetic field weakens to \( B_s \sim 10^7 - 10^8 \) Gauss. For both IMBPs and LMBPs the endpoint is a pulsar in an almost circular orbit, and the most common companion is a white dwarf, the mass and chemical composition of which depends on the original companion mass and orbital period. In particular Tauris (2011) classifies 3 main paths for the formation of IMBPs and 2 roads for the LMBPs (see Table 1 of Tauris 2011). Tauris, Langer & Kramer 2012 also report in Appendix a Table which can be used as a sort of \textit{finding chart} for guessing the most likely nature of the companion to a pulsar, on the basis of the observed constraints on orbital period, eccentricity and mass of the companion.

3.1. Classical tests for LMBPs with a He-WD companion

There exist two well known predictions of the standard evolutionary models for the case of the LMPBs with a He-WD companion: \( (i) \) a correlation between eccentricity and orbital period (see Phinney 1992 for the underlying physical explanation) and \( (ii) \) a correlation between the orbital period and the companion mass (see e.g. Tauris & Savonije 1999 and references therein for the rationale beyond that). A recent analysis (Barr \textit{et al.} (2012)) confirms that the relation \( (i) \) is in general in agreement with the observations, although the spread in the data is slightly larger than predicted (see Fig. 2, left panel).

As to the correlation \( (ii) \), some discrepancy with the observations was noticed for the binaries with longer orbital periods, but in fact the theoretical predictions can be reconciled with the available data if the correlation is drawn for a distribution of pulsar masses (between 1.3 and 2 \( M_\odot \)) instead than for a single mass (Shao & Li 2012). However, the

\[ \text{Figure 2. Left panel: the correlation between eccentricity and orbital period for LMBPs with He-WD companions not included in globular clusters (GCs). The dashed lines should enclose the 95\% of the observed binaries (Phinney & Kulkarni 1994). Current data show that this is the case for the 75\% of the objects (adapted from Barr \textit{et al.} (2012)). Right panel: The correlation between orbital period and companion mass for the 6 LMBPs for which the mass of the He-WD companion has been obtained via the observation of the Shapiro delay in the times of arrival of the pulses from the pulsar. The three lines refer to the Tauris & Savonije (1999) relation for various ensembles of stellar populations (adapted from Corongiu \textit{et al.} 2012).} \]
capability of the correlation to really constrain the models is in general hampered by the usually very large uncertainties on the observed mass of the He-WD companion. More useful results can be obtained focusing on subsets of binaries for which accurate determination of the companion mass have been obtained. For example, in Fig. 2 (right panel) shows all binaries for which the He-WD mass has been derived from the measurement of the Shapiro-delay effect in the system.

3.2. Some noteworthy cases of study: unveiled links, new species, new ideas

**J1023+0038**: is a 1.69-ms fully recycled pulsar in a 4.75-hr circular orbit with a $\sim 0.25 M_\odot$ main sequence companion, displaying extended radio eclipses, X-ray orbital modulation and $\gamma$-ray emission (Archibald et al. 2009, 2010; Tam et al. 2010; Bogdanov et al. 2011). The so far unique feature of this binary is that there are evidences for it to have hosted an accretion disk until around 2001 (Wang et al. 2009). The system may thus currently be in a bi-stable status, switching among a X-ray accreting phase and a non-accreting radio emitting phase. In view of this characteristics, the binary may likely represent the long sought link between the largest subgroup of the LMBPs (those with a He-WD companion) and their supposed progenitors, i.e. the Low Mass X-ray Binaries (LMXBs). The recent measurement of the parallax distance of the system (1370±40 pc, Deller et al. 2012) and the related updated determination of the pulsar mass ($1.71\pm0.16 M_\odot$) open the possibility of a largely improved modeling of the last stages of the recycling with emphasis on the interaction between the pulsar wind and the matter lost by the companion. In fact, given the features of the radio eclipses and the parameters of the system, PSR J1023+0038 also represents a stereotype for the so-called Red Back pulsars (see Roberts’ contribution to this volume).

**J1719−1438**: This is a 5.7-ms fully recycled pulsar, orbiting in 2.2 hr a Jovian-mass companion (as indicated by the very small pulsar mass function) having a minimum average density $> 23$ g cm$^{-3}$, significantly larger than what observed in planets (Bailes et al. 2011). That suggests that it represents the first unambiguous case - and thus the prototype - of a recycled pulsar descending from a so-called Ultra Compact Accreting X-ray Millisecond Pulsar (UC-AXMSP, for a review see e.g. Patruno & Watts 2012), i.e. X-ray binaries containing a rapidly spinning neutron star and a very low mass companion (typically few hundredths of solar masses) in ultra compact systems with orbital period from $\sim 40$ min to $\sim 80$ min. More recent investigations by Haaften et al. (2012; also this volume) and by Benvenuto et al. (2012) have supported the aforementioned evolutionary connection between the J1719−1438 binary and the UC-AXMSPs, although some additional ingredients (e.g. a combination of wind mass loss and expansion of the donor) are necessary for explaining all the features of the system (see also Horvath 2012, and Weber, this volume, for a more exotic explanation of J1719−1438).

**ULMBPs**: It is very intriguing that J1719−1438 is not a unique case anymore: two additional fully recycled pulsars with a Jovian-mass companion have emerged among the very recent discoveries of the ongoing pulsar surveys (see Ng; Lynch; both this volume). Therefore it is tempting to introduce a new subclass in the family of the LMBPs with short orbital period ($\lesssim 1$ day), which may be dubbed Ultra Low Mass Binary Pulsars (ULMBPs) : these could be characterized by ultra small values ($x < 0.01$ sec) of the quantity $x = a_p/c$, where $a_p$ is the projected semi-major axis of the pulsar orbit and $c$ is the speed of light. Assuming that the orbit is not almost face-on, those values of $x$ translate in a companion mass within the range $\sim 0.001 M_\odot \rightarrow \sim 0.01 M_\odot$.

The distinct nature of the progenitors would be a good reason for distinguishing the new class of the ULMBPs from that of the so-called Very Low Mass Binary Pulsars (VLMBPs: short orbital period pulsars with $0.01$ sec $\lesssim x \lesssim 0.1$ sec and corresponding
companion masses in the range $\sim 0.01 M_\odot \rightarrow \sim 0.1 M_\odot$). In fact, VLMBPs cannot be truly descendent of the UC-AXMSPs, since the companion masses are typically larger in VLMBPs than in UC-AXMSPs and the mass of the companion cannot ever increase during the evolution of these binaries†.

**Isolated recycled pulsars:** The mechanism leading to the formation of the isolated fully recycled pulsars is not yet clarified. Ablation and finally evaporation of a low mass companion by the pulsar’s energetic flux was proposed early (see e.g. Ruderman et al. 1989). The discovery of the eclipsing binary pulsars, and in particular the class of the so-called Black Widows (Fruchter, Stinebring & Taylor; see Roberts’ contribution, this volume, for an updated list) seemed to strongly corroborate this hypothesis. However, various observations indicate that the timescale for the evaporation process may be too long (i.e. larger than a Hubble time) for considering the observed systems as progenitors of the isolated recycled pulsars (e.g. Stappers et al. 1996). Alternatively, the companion star in a ULMBP could eventually disrupt for the insurgence of internal instability when its mass becomes too small (Deloye & Bildsten 2003).

Until recently, the VLMBPs (the family which the Black Widows belong to) were mostly found in GCs, where the formation of isolated pulsars can easily occur via ionization of a binary following a dynamical encounter (see Freire; Belfiore; both this volume). Now, the blossom of discoveries of VLMBPs/ULMBPs, as well as of isolated recycled pulsars in the Galactic field, starts eventually enabling a direct statistical comparison of the two populations, aiming to search for relationships and putative evolutionary connections (Possenti et al, in preparation).

**J1614−2230:** is a 3.15-ms fully recycled pulsar in a 8.7-day almost circular and highly inclined orbit with a $\sim 0.500 \pm 0.006 M_\odot$ white dwarf companion. The inferred mass of the pulsar, $1.97 \pm 0.04 M_\odot$, (Demorest et al. 2010) makes it the most massive neutron star known to date, providing a discriminant test for few proposed equation of state for the nuclear matter. The accurate determination of the geometry of the orbit and of the masses of the binary components was made possible by the accurate measurement of the Shapiro delay. Besides the impact on nuclear physics, the J1614−2230 system is very interesting also as far as binary evolution studies. The companion mass and the orbital period clearly suggest that it belongs to the class of the IMBPs, however the rapid spin period is at odds with the mild recycling which is expected for these pulsars. Tauris, Langer & Kramer (2011, 2012) solved the issue showing that J1614−2230 descended from a previously overlooked formation path for the IMBPs: i.e. evolution in a close binary system with a 4−5 $M_\odot$ main sequence donor star via Case A Roche Lobe Overflow (see also Lin et al. 2011 and Bhalerao & Kulkarni 2011). Given this model, it is possible to constrain the original mass of the pulsar (i.e. immediately after the supernova explosion and prior any accretion): the resulting $(1.7 \pm 0.15) M_\odot$ is significantly larger than what was measured in e.g. the double neutron star binaries and is relevant for the investigation of the physics of the core-collapse supernova.

**J1903+0327:** is a 2.1-ms fully recycled pulsar, orbited by a $\sim 1 M_\odot$ main sequence star in a 95.2-day orbit, with a high eccentricity $e = 0.44$ (Champion et al. 2008). Based on these observables, this binary could hardly be formed via the standard recycling mechanism, which should have led to an almost circular orbit. Freire et al. 2011 showed that the most viable hypothesis is that the neutron star was in a close orbit with a main sequence star and the current companion was a tertiary farther out. After having spun up the pulsar, the inner companion vanished, maybe due to a chaotic three-body interaction

† An exception could result from the evolution of a triple system, but no observational hint of the presence of a third star has been collected so far in the observed UC-AXMSPs.
with the outer star or due to ablation by the newly recycled pulsar. Similar conclusions have been derived by various other authors (e.g.: Portegies Zwart et al. 2011, Bejger et al. 2011, Pijloo, Caputo & Portegies Zwart 2012, Khargharia 2012). After many years for which it was mostly a theoretical exercise, first the discovery of J1903+0327 and now (see Lazarus’s contribution) that of a truly triple system in the Galactic field, promise to open the doors of a new gym for evolutionary and dynamical studies.

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Surrounded by spiders! New black widows and redbacks in the Galactic field

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Abstract.
Over the last few years, the number of known eclipsing radio millisecond pulsar systems in the Galactic field has dramatically increased, with many being associated with Fermi gamma-ray sources. All are in tight binaries (orbital period < 24 hr) with many being classical “black widows” which have very low mass companions (companion mass \( M_c < 0.1 \text{M}_\odot \)) but some are “redbacks” with low mass (\( M_c \sim 0.2 - 0.4 \text{M}_\odot \)) companions which are probably non-degenerate. These latter are systems where the mass transfer process may have only temporarily halted, and so are transitional systems between low mass X-ray binaries and ordinary binary millisecond pulsars. Here we review the new discoveries and their multi-wavelength properties, and briefly discuss models of shock emission, mass determinations, and evolutionary scenarios.

Keywords. binaries: close, pulsars: general, binaries: eclipsing, shock waves, gamma rays: observations, acceleration of particles, accretion, equation of state, pulsars: individual (PSR J2129-0429), X-rays: binaries

1. Introduction
In 1962, Giacconi and collaborators discovered the first low mass X-ray binary (LMXB) Sco X-1, thought to be a neutron star in an 18.9 hr orbit accreting from a \( \sim 0.4 \text{M}_\odot \) companion (Steeghs & Casares 2002). Shortly after the discovery of the first millisecond radio pulsar (MSP) PSR B1937+21, Alpar et al. (1982) proposed that radio MSPs were the end product of the accretion process we are observing in LMXBs. Of the roughly 2000 radio pulsars known today, about 10% are MSPs, old neutron stars which have been spun-up, or “recycled”, through accretion of material from a companion. Many details of this recycling process remain unknown, but it is clear that most fast-spinning (\( P < 8 \text{ ms} \)) MSPs have degenerate white dwarf companions with masses between 0.1 and 0.4 \( \text{M}_\odot \), and very tightly follow the expected correlation between companion mass and orbital period derived from binary evolution models (see Figure 1). However, some (up to 20%) of MSPs are isolated. The process through which these MSPs were formed is unclear. Did they somehow lose their companions or were they born through a different formation channel? One idea is that the companions of isolated MSPs were ablated away by energetic particles and/or \( \gamma \)-rays produced by the pulsar wind. This idea was inspired by the discovery of the original “Black Widow” pulsar, B1957+20 (Fruchter, Stinebring & Taylor 1988), an eclipsing 1.6 ms pulsar in a 9.1-hr orbit around a very low mass (\( M_C \sim 0.02 \text{M}_\odot \)) companion.

The accretion formation scenario has been strongly supported by observations of fast X-ray millisecond pulsations in transient LMXBs and Type I X-ray bursts (see “Compact Stellar X-ray Sources” eds. Lewin and van der Klis for reviews). The “missing link” of the MSP formation scenario, PSR J1023+0038, was discovered in a Green Bank Telescope
Figure 1. Minimum companion mass vs. orbital period of fast \(P < 8\) ms binary MSPs in the Galactic field, showing the positions of the Redbacks and Black Widows discussed in this proceedings. The lines are from various binary evolution models considered by Tauris & Savonije (1999) which result in a Helium white dwarf companion. Since we plot minimum companion masses, we expect systems which evolved according to standard evolutionary scenarios be just to the left of these lines. Note the one clear, non-spider exception at multi-day periods is PSR J1614−2230, which has a CO white dwarf companion and is a major challenge to current models (eg. Tauris, Langer & Kramer 2011). Non-spider MSPs (plus signs) are from the ATNF pulsar catalog \texttt{http://www.atnf.csiro.au/research/pulsar/psrcat}

Drift scan pulsar survey (Archibald et al. 2009). This 1.69 ms radio pulsar is in a 4.8 hr orbit around an \(~0.2M_\odot\) non-degenerate companion, and exhibits regular radio eclipses around superior conjunction. Optical spectra taken in 2001 of the system, before radio pulsations were discovered, showed emission lines indicating the presence of an accretion disk but observations in 2004 showed only absorption lines suggesting the accretion disk had vanished (Wang et al. 2009). X-ray studies with XMM-Newton (Archibald et al. 2010) and Chandra (Bogdanov et al. 2011) show significant orbital modulation in addition to pulsations, presumably arising from an intrabinary shock. The eclipse depth and duration imply that the shock is localized near or at the surface of the companion. The energetics favor a magnetically dominated pulsar wind that is focused into the orbital plane, requiring close alignment of the pulsar spin and orbital angular momentum axes as expected. The X-ray spectrum consists of a dominant non-thermal component from the shock and at least one thermal component, likely originating from the heated pulsar polar caps. This source has become the prototype of the \textit{redback} systems, named after the Australian cousin to the North American black widow. Although having similar energetics, orbital periods, and eclipses, redbacks tend to have companions whose masses are higher than the expected white dwarf endpoint for their orbital period, rather than much lower as for the black widow like pulsars (see Figure 1).

For both PSR B1957+20 and PSR J1023+0038, orbital modulation of the illuminated optical companions show that they are nearly filling their Roche lobes (van Kerkwijk et al. 2011, Deller et al. 2012). Optical studies have been used to estimate the inclination angles and masses of the neutron stars, which are well above the canonical \(1.4M_\odot\).

In principle, these systems should be excellent for studying the acceleration, composition, and shock dynamics of the highly relativistic winds coming from energetic pulsars (Arons & Tavani 1993). In particular, in terms of light cylinder radii, the intrabinary shocks in these systems are tens of thousands of times closer than the termination shock
of young pulsar wind nebulae like the Crab. This means that we can probe the pulsar wind in regions where the magnetization parameter of the ultra-relativistic wind $\sigma$ may still be relatively high.

Deep pulse searches of globular clusters over the years have yielded 18 binary pulsars with very low, black widow like, companion masses. They also yielded 12 short orbit eclipsing systems with more ordinary companion masses often showing optical evidence of a non-degenerate companion, i.e. redback like systems (see P. Freire’s webpage http://www.naic.edu/~pfreire/GCpsr.html for a complete list of globular cluster MSPs). Unfortunately, studies of the energetics, X-ray properties, and optical companions of globular cluster pulsars are difficult due to the crowded fields, the on average large distance, and the gravitational well of the cluster often making the intrinsic spin-down rate impossible to infer. Nearby systems in the Galactic field are therefore desirable for detailed studies.

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<th>$P_s$ (ms)</th>
<th>$E/10^{34}$ $^2$ (erg/s)</th>
<th>$d_{NGC2001}$ (kpc)</th>
<th>$P_B$ (hr)</th>
<th>$M_c$ $^3$ (solar)</th>
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<th>$E/10^{34}$ $^2$ (erg/s)</th>
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Table 1. Black Widows and Redbacks in the Galactic Field

$^1$ an F indicates a Fermi source. $^2$ assuming $1.4M_\odot$ and 10 km radius. $^3$ assuming $1.4M_\odot$ pulsar and $i = 90^\circ$.

However, for the 20 years between the discovery of PSR B1957+20 and PSR J1023+0038, eclipsing MSPs remained rare outside of globular clusters. Only two black widow like systems were discovered during this time period, both with relatively low spin-down energies. Radio surveys sensitive to fast pulsars in tight binaries have recently greatly increased the number of known black widows and redbacks in the Galactic field (see Table 1). Surveying high-latitude Fermi $\gamma$-ray sources has proven to be the most productive means of discovering new MSPs, with 43 discovered so far (Ray et al. 2012). A surprising fraction of these new MSPs have turned out to be eclipsing sources in compact (< 1 day) orbits.
All told, there are more than 12 new black widows and 6 new redbacks that have been discovered in the Galactic field over the last 3 years.

Timing of these systems is complicated by a tendency for their pulse profiles to vary as a function of frequency. For example, the redback PSR J2215+5135 discovered in a 350 MHz Green Bank Telescope survey of Fermi sources (Hessels et al. 2011) shows a double pulse profile at 350 MHz, but by 2 GHz is predominantly single peaked, which peak is neither of the peaks seen at 350 MHz. Eclipse fractions also vary significantly as a function of frequency. Most of the systems show some amount of change in orbital period, presumably from the mass quadrupole moment of the companion. Long term monitoring of these orbital variations may serve as a unique probe of the stellar structure of their companions. Optical studies of the companions show they are often close to filling their Roche lobes, and so can be significantly non-spherical (Breton et al. 2012).

An unfortunate aspect of these changes in orbital period is that it is often problematic to extrapolate timing solutions back to the beginning of the Fermi mission to allow the most sensitive γ-ray pulse studies. Despite this, once a lengthy enough timing solution is obtained, folding the Fermi γ-ray data has usually resulted in a pulsed detection above 100 MeV.

X-ray studies of these new systems show that they tend to have an orbitally modulated, non-thermal component to their X-ray emission (Gentile et al. 2012). This is presumably due to the intrabinary shock. Current studies are statistically limited, however, and deeper X-ray observations are needed for detailed studies. So far, there has been no strong evidence of orbital modulation of the γ-ray emission detected by Fermi, and only upper limits have been obtained from TeV observations.

Optical studies have shown that both types of systems show evidence of bloated companions, with Roche lobe filling factors \( \sim 0.4 - 1.0 \) (Breton et al. 2012). By combining light curve modelling and radial velocity measurements of photospheric lines, the geometry of the systems and strong mass constraints on the components can be obtained. The distinctive optical light curves can be used to identify systems whose radio pulsations cannot be detected, either due to radio beaming or having a 100% eclipse fraction. Indeed, there have already been a few such systems discovered (Kong et al. 2012, Romani & Shaw 2011).

Neither black widows nor redbacks seem to be the end products of standard binary evolution models. However, at least for redbacks, it seems clear that the companions are not yet degenerate, and so may be systems where the recycling process is temporarily halted, but will resume in the near future. The position of redbacks on the companion mass–orbital period diagram (Figure 1) is intriguingly consistent with model evolutionary tracks of systems whose endpoints are ultra-compact X-ray binaries (Podsiadlowski et al. 2002). Black Widows, however, seem to occupy positions on the diagram which no evolutionary tracks pass through.

The suppression and decay of the magnetic field from \( B \sim 10^{12} \) G down to \( \sim 10^8 \) G during the accretion process is still not well understood, but must happen for pulsars to be spun-up to periods shorter than a few milliseconds (Cumming 2005). There is, however, an empirical relationship between the spin period of a MSP and its magnetic field inferred from its spin-down. For MSPs with white dwarf companions, billions of years may have passed since the recycling process ended, and significant spin down will typically have occurred. If redbacks are systems in which the recycling process is only temporarily interrupted, then we might expect them to be very nearly maximally spun-up for their magnetic field. In Figure 2, we show this empirical relationship, and indeed, redbacks tend to be among the fastest spinning of MSPs for a given magnetic field. Note that the magnetic field inferred from spin-down assumes pure dipole radiation,
The accelerated rate of discovery of new eclipsing systems is likely to continue for several more years, as more results come in from ongoing large scale pulsar surveys and more *Fermi* sources are discovered and searched. Radio, optical, X-ray, and γ-ray studies all hold much potential for discovery. Well constrained pulsar masses, insights into the recycling process, unique tests of particle particle acceleration models, and even greater

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**Figure 2.** Spin period vs. inferred surface magnetic field for fast MSPs in the Galactic field. In the case of no magnetic field decay after accretion stops, pulsars near maximum spin-up should be to the left of average for a given magnetic field. Note that not all pulsars in this diagram have had their spin-downs corrected for their motion in the Galaxy, which means that their magnetic fields would be overestimated. Also, variations in moments of inertia (i.e. different pulsar masses) and magnetic inclination angles would also affect the inferred magnetic field in the standard dipole approximation.

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One of the new redback systems is particularly noteworthy as having both the largest minimum companion mass and largest inferred magnetic field. PSR J2129−0429 was also discovered in the 350 MHz Green Bank Telescope survey of *Fermi* sources. It shows extensive radio eclipses and has a bright UV counterpart seen with the Swift UVOT. The Swift X-ray data suggest strong orbital modulation, and that it may have the brightest X-ray shock emission of any of the known eclipsing binaries. Its orbit and companion mass are actually quite similar to that of Sco X-1. If nearly filling its Roche lobe, the companion would only be ~ 8000 light cylinder radii away from the pulsar. Further studies of this system may give us a unique window into the earlier stages of the recycling process.

The dramatic increase in the number of systems with intrabinary pulsar wind shocks may herald a new era of pulsar wind studies. The recent evidence of dramatic GeV-TeV flaring in the high mass radio pulsar binary PSR B1259−63 demonstrates the potentially strong geometrical dependence of high energy emission from pulsar wind shocks (Abdo et al. 2011). While the binary separation and nature of the companion is very different between PSR B1259−63 and the eclipsing MSPs, the spin-down fluxes are within an order of magnitude, and the density of photons available for Compton up-scattering from the companion at the shock is actually fairly similar. Therefore, they may prove to be a new class of TeV sources, either to the current generation of instruments or to CTA.

The accelerated rate of discovery of new eclipsing systems is likely to continue for several more years, as more results come in from ongoing large scale pulsar surveys and more *Fermi* sources are discovered and searched. Radio, optical, X-ray, and γ-ray studies all hold much potential for discovery. Well constrained pulsar masses, insights into the recycling process, unique tests of particle particle acceleration models, and even greater
understanding of the structure of evolved low-mass stars may all result from current work on these new systems.

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Formation of the planet orbiting the millisecond pulsar J1719–1438

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Abstract. In 2011, Bailes \textit{et al.} reported on the discovery of a detached companion in a 131 minute orbit around PSR J1719–1438, a 173 Hz millisecond pulsar. The combination of the very low mass function and such a short orbital period is unique. The discoverers suggested that the progenitor system could be an ultracompact X-ray binary (UCXB), which is a binary with a sub-hour orbital period in which a (semi-)degenerate donor fills its Roche lobe and transfers mass to a neutron star. The standard gravitational-wave driven UCXB scenario, however, cannot produce a system like PSR J1719–1438 as it would take longer than the age of the Universe to reach an orbital period of 131 min. We investigate two modifications to the standard UCXB evolution that may resolve this discrepancy. The first involves significant heating and bloating of the donor by pulsar irradiation, and in the second modification the system loses orbital angular momentum via a fast stellar wind from the irradiated donor, additional to the losses via the usual gravitational wave radiation. In particular a donor wind is effective in accelerating orbital expansion, and even a mild wind could produce the 131 minute period within the age of the Universe. We note that UCXBs could be an important class of progenitors of solitary millisecond radio pulsars.

Keywords. pulsars: individual (PSR J1719–1438), stars: mass loss, binaries: close, planets and satellites: formation, X-rays: binaries

1. Introduction

PSR J1719–1438, with a 5.8 ms spin period, was found to be orbited every 131 min by a companion (Bailes \textit{et al.} 2011). The mass function of $\sim 10^{-9} M_\odot$ implies that in the (a priori) very likely case that we do not observe the PSR J1719–1438 system close to face-on, the companion must have a mass of the order of $\sim 10^{-3} M_\odot$. This system is very interesting because almost all millisecond radio pulsars either have a stellar-mass companion or no companion at all. There are black widow X-ray binaries with similar orbital periods but those are semi-detached and have much more massive companions. The system is detached, and from its orbital period a minimum average density of the companion of $23 \text{ g cm}^{-3}$ can be derived.

2. Composition of the companion

In Fig. 1 we show the constraints on the companion set by its minimum density (i.e., its Roche-lobe radius at a given mass, which is the maximum radius), and the radii of zero-temperature white dwarfs of different compositions, which give the minimum radius.
We see that a carbon-oxygen composition is the most likely, followed by helium, but that requires an inclination with an a priori probability near 14%, or less in case of a finite-temperature companion. Hydrogen is possible if we see the systems nearly face-on, with an a priori probability near 0.1%.

3. Ultracompact X-ray binary scenario

Bailes et al. (2011) suggested that this system could have evolved from an ultracompact X-ray binary (UCXB), which consists of a (semi-)degenerate donor transferring mass to a neutron star, driven by angular momentum loss via gravitational wave radiation (e.g. Savonije et al. 1986). The mean donor density is one-to-one related to the orbital period, as it always the case for a Roche-lobe filling star with a more massive companion. Therefore, as the donor loses mass and becomes less dense, the orbit expands, and the mass transfer rate decreases. However, UCXBs are expected to reach orbital periods of at most 90 min within the age of the Universe (Deloye & Bildsten 2003).

We discuss two modifications to this standard UCXB scenario that could explain how they could reach an orbital period of 131 min. The first is a relatively large donor size, the second is a stellar wind from the donor. Both are caused by heating and irradiation of the donor by the accretion disk, accretor, and magnetosphere.

4. Increased donor size

The size of the donor in an UCXB influences the mass transfer rate. A larger (‘bloated’) donor with respect to the zero-temperature radius implies a higher mass is required to have a given average density, which corresponds to an orbital period, as mentioned before. A higher donor mass in turn implies a higher mass transfer rate and faster evolution. In Fig. 2 is shown that UCXBs with relatively large donors can reach a period of 131 within the age of the Universe. However, the donor mass would be about ten times larger than

![Figure 1](image_url) Mass-radius relations for zero-temperature white dwarfs (Rappaport et al. 1987) for pure helium, carbon and oxygen (dashed), and the relation between the Roche-lobe radius and the mass of the companion of PSR J1719–1438 (solid). Filled circles (1.4 \( M_\odot \) neutron star) and open circles (2 \( M_\odot \) neutron star) indicate the 1, 0.1 and 0.01 a priori probabilities that the companion mass is higher than indicated. Figure from van Haaften et al. (2012a).
5. Stellar wind from the donor

In a binary, the specific angular momentum is highest in the lowest-mass component. At the extreme mass ratio found in UCXBs, a large amount of angular momentum can be lost by systems if the donor loses matter in a fast, isotropic wind. Such a wind can be caused by irradiation of the donor. Fig. 3 shows that a relatively low wind mass loss rate during the entire evolution is already enough to speed the orbital expansion to a period of 131 min within the age of the Universe.

Long-term observations by the Rossi XTE All-Sky Monitor show that most of the UCXBs with orbital periods longer than 40 min are one to two orders of magnitude brighter than expected when their mass transfer was driven only by angular momentum loss via gravitational wave radiation (van Haaften et al. 2012c). Also, Knigge et al. (2011) found that Cataclysmic Variables below the period gap evolve faster than expected from gravitational wave emission only. This suggests that they indeed evolve faster, which supports the hypothesis that PSR J1719–1438 is an UCXB descendant.


The present detached state of the system may be caused by the gradually decreasing irradiation, which could result in the donor shrinking inside its Roche lobe. Then the accretion rate would decrease, further decreasing the level of donor irradiation.

![Figure 2](image_url)

**Figure 2.** Donor mass versus orbital period for UCXBs based on tracks by van Haaften et al. (2012b). The solid curves show the evolution of UCXBs with zero-temperature white dwarf donors. The dashed curves show the same except that the donors have twice as large radii at all masses. The circles and numbers mark ages in yr. Filled (open) symbols correspond to an initial accretor mass of 1.4 $M_\odot$ (2 $M_\odot$). The dotted parts of the curves take longer than the age of the Universe to reach. The vertical line is located at the orbital period of PSR J1719–1438, and the triangles mark the a priori probabilities that the donor mass is higher than indicated, based on the mass function. Figure adapted from van Haaften et al. (2012a).
PSR J1719–1438 very likely has a low-mass companion, composed mainly of carbon/oxygen or possibly helium. Its orbital period of 131 min could have been reached by an ultracompact X-ray binary whose late-time evolution was driven by angular momentum loss via a stellar wind from the donor, rather than the emission of gravitational waves, which subsequently became detached. A wind of $\gtrsim 3 \times 10^{-13} \, M_\odot \, yr^{-1}$ would be sufficient. The composition of the companion is most likely carbon-oxygen, though helium cannot be ruled out.

Old UCXBs are expected to have very low donor masses (below $\sim 0.01 \, M_\odot$). If PSR J1719–1438 has indeed formed out of an UCXB, then we would expect to see more binary millisecond radio pulsars with very low mass companions. Such systems are very rare though, whereas solitary millisecond radio pulsars are relatively common. This suggests the possibility that low-mass companions of UCXBs are completely evaporated (Ruderman et al. 1989), leaving a population of solitary millisecond radio pulsars.

References
Recycling Pulsars: spins, masses and ages

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Abstract. Although the first millisecond pulsars (MSPs) were discovered 30 years ago we still do not understand all details of their formation process. Here, we present new results from Tauris, Langer & Kramer (2012) on the recycling scenario leading to radio MSPs with helium or carbon-oxygen white dwarf companions via evolution of low- and intermediate mass X-ray binaries (LMXBs, IMXBs). We discuss the location of the spin-up line in the $P\dot{P}$-diagram and estimate the amount of accreted mass needed to obtain a given spin period and compare with observations. Finally, we constrain the true ages of observed recycled pulsars via calculated isochrones in the $P\dot{P}$-diagram.

Keywords. stars: neutron, pulsars: general, white dwarfs, X-rays: binaries

1. Introduction

Binary MSPs represent the advanced phase of stellar evolution in close, interacting binaries. Their observed orbital and stellar properties are fossil records of their evolutionary history. Thus one can use binary pulsar systems as key probes of stellar astrophysics. Although the standard recycling scenario (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991) is commonly accepted, many aspects of the mass-transfer process and the accretion physics are still not understood in detail. Examples of such ambiguities include the accretion disk structure, the disk-magnetosphere transition zone, the accretion efficiency, the decay of the surface B-field of the neutron star and the outcome of common envelope evolution. For further details on these aspects, details in general and discussions of our results, we refer to our journal paper, Tauris et al. (2012).

2. The spin-up line

Some of the above mentioned simplifications become a problem when trying to probe the formation and the evolution of observed recycled radio pulsars located near the classical spin-up line for Eddington accretion in the $P\dot{P}$-diagram (e.g. as illustrated with the MSP J1823–3021A, Freire et al. 2011). The location of the spin-up line can be found by considering the equilibrium configuration when the angular velocity of the neutron star is equal to the Keplerian angular velocity of matter at the magnetospheric boundary ($r_{\text{mag}}$) where the accreted matter enters the magnetosphere, i.e. $\Omega_\star = \Omega_{\text{eq}} = \omega_c \Omega_K(r_{\text{mag}})$ or: $P_{\text{eq}} = 2\pi (r_{\text{mag}}^3 \dot{M}/GM)^{1/2} \omega_c^{-1}$, where $0.25 < \omega_c \leq 1$ is the so-called critical fastness parameter. Introducing the magnetospheric coupling radius, $\phi \equiv r_{\text{mag}}/r_{\text{Alfven}}$ and the magnetic inclination angle, $\alpha$ we can rewrite this expression:

$$\dot{P} = \frac{2^{1/6} G^{5/3} \dot{M} M^{5/3} P_{\text{eq}}^{4/3}}{\pi^{1/3} c^3} \frac{I}{(1 + \sin^2 \alpha) \phi^{-7/2} \omega_c^{7/3}}$$ (2.1)
which can be plotted directly in the $P\dot{P}$-diagram. (Here $M$ is the mass of the pulsar, $\dot{M}$ is its accretion rate and $I$ is its moment of inertia.) In case $\sin \alpha = \phi = \omega_c = 1$ we find:

$$\dot{P} = 3.7 \times 10^{-19} \left( \frac{M}{M_\odot} \right)^{2/3} P_{\text{ms}}^{4/3} \frac{\dot{M}}{M_{\text{Edd}}}$$

(2.2)

where $P_{\text{ms}}$ is the equilibrium spin period in units of milliseconds. We have included the plasma term in the spin-down torque using the combined model of Spitkovsky (2006) to compensate for the incompleteness of the vacuum magnetic dipole model.

In Fig. 1 we have plotted equation (2.1) for different values of $\alpha$, $\phi$ and $\omega_c$ to illustrate the uncertainties in the applied accretion physics to locate the spin-up line. In all cases we assumed a fixed accretion rate of $\dot{M} = M_{\text{Edd}}$. The location of the spin-up line is simply shifted one order of magnitude in $\dot{P}$ down (up) for every order of magnitude $M$ is decreased (increased). It is important to realize that there is no universal spin-up line in the $PP$-diagram. Not only are $M$ and $\alpha$ individual to each pulsar (giving rise to the width of each band), also $\phi$ and $\omega_c$ could be related to $B$, $\alpha$ and $M$. If we assume that accretion onto the neutron star is indeed Eddington limited, then the three bands in Fig. 1 represent upper limits for the spin-up line for the given sets of $(\phi, \omega_c)$. Thus we can in principle use this plot to constrain $(\phi, \omega_c)$ and hence the physics of disk–magnetosphere interactions from future detections of MSPs.

Figure 1. Calculations of three spin-up lines, shown as coloured bands, depending on the parameters $(\phi, \omega_c)$. The upper boundary of each band (or “line”) is calculated for a neutron star mass $M = 2.0 M_\odot$ and $\alpha = 90^\circ$. The lower boundary is calculated for $M = 1.0 M_\odot$ and $\alpha = 0^\circ$. The green (central) hatched band corresponds to $\phi = 1$ and $\omega_c = 1$. The blue and red hatched bands are upper and lower limits set by reasonable choices of the two parameters $(\phi, \omega_c)$. In all three cases the spin-up line is calculated assuming accretion at the Eddington limit, $\dot{M} = M_{\text{Edd}}$. The observed distribution of binary and isolated radio pulsars in the Galactic disk are plotted as filled and open circles, respectively. Also plotted is the pulsar J1823–3021A, located in the globular cluster NGC 6624. (Fig. adapted from Tauris et al. 2012.)
When modeling the birth spins of recycled radio pulsars it is important to include the braking torque acting during the Roche-lobe decoupling phase (RLDP) when the donor star terminates its mass transfer. It has been shown that accreting X-ray MSPs may lose up to 50% of their rotational energy during the RLDP of LMXBs (Tauris 2012).

3. Relation between accreted mass and final spin period

Recycled pulsars obtain their fast spins via angular momentum exchange from the differential rotation between the accretion disk and the neutron star. The amount of spin angular momentum added to an accreting pulsar is given by:

$$\Delta J = \int n(\omega, t) \dot{M}(t) \sqrt{GM(t) r_{\text{mag}}(t) \xi(t)} \, dt$$  \hspace{1cm} (3.1)

where $n(\omega, t)$ is a dimensionless torque. Assuming $n(\omega, t) = 1$, and $M(t)$, $r_{\text{mag}}(t)$ and $\xi(t)$ to be roughly constant during the major part of the spin-up phase we can obtain a simple and convenient expression to relate the (minimum) amount of accreted mass and final equilibrium spin period (see also Alpar et al. 1982):

$$\Delta M_{\text{eq}} = 0.22 M_\odot \frac{(M/M_\odot)^{1/3}}{P_{\text{ms}}^{4/3}}$$  \hspace{1cm} (3.2)

assuming a numerical factor $f(\alpha, \xi, \phi, \omega_c) = 1$ (from disk-magnetosphere interactions).

Considering a pulsar with a final mass of $1.4 M_\odot$ and a recycled spin period of either 2 ms, 5 ms, 10 ms or 50 ms requires accretion of $0.10 M_\odot$, $0.03 M_\odot$, $0.01 M_\odot$ or $10^{-3} M_\odot$, respectively. Therefore, it is no surprise that observed recycled pulsars with massive companions (CO/ONeMg WD or NS) in general are much more slow rotators – compared to MSPs with He WD companions – since the progenitor of their massive companions evolved on a relatively short timescale in IMXBs or HMXBs, only allowing for very little mass to be accreted by the pulsar.

4. True age isochrones of recycled pulsars

In order to investigate if we can understand the distribution of MSPs in the $P\dot{P}$-diagram we have traced the evolution of eight hypothetical, recycled MSPs with different birth locations ($P_0$, $\dot{P}_0$). In each case we traced the evolution as a function of age, $t$ for a constant braking index $2 \leq n \leq 5$ and calculated isochrones by integration for each pulsar given that $P(t, n, P_0, \dot{P}_0)$. The results are shown in Fig. 2 together with observed data. Furthermore, we plotted two isochrones (see fat green and pink lines) calculated for $(P_0 = 1.0 \text{ ms}, n = 3, t = 1.5 \text{ Gyr})$ and $(P_0 = 7.0 \text{ ms}, n = 3, t = 12 \text{ Gyr})$, respectively, and with no restrictions on $\dot{P}_0$ (or $B_0$).

A number of interesting conclusions can be drawn from this diagram. The overall distribution of observed pulsars follows nicely the banana-like shape of the two fat isochrones, see also Kiziltan & Thorsett (2010), and hence pulsars are recycled with a wide range of final B-fields. Although these curves are not an attempt for a best fit to the observations it is interesting to notice that close to 90% of all recycled pulsars (even up to $P = 100 \text{ ms}$) are compatible with being born (recycled) with an initial spin period of $P_0 = 1 – 7 \text{ ms}$ and having ages between 1.5 and 12 Gyr. However, from a binary evolution point of view many of the $P = 20 – 100 \text{ ms}$ pulsars (the mildly recycled pulsars) are born with such relatively slow spins (see Section 3) and hence they need not be that old. This can, for example, be verified by cooling age determinations of their WD companion stars. Pulsars with small values of the period derivative, $\dot{P} \approx 10^{-21}$ hardly evolve at all in
Figure 2. Isochrones of eight hypothetical recycled pulsars born at the locations of the red stars. The isochrones were calculated for different values of the braking index, $2 \leq n \leq 5$. Also plotted are inferred $B$-field values (dashed lines) and characteristic ages, $\tau$ (dotted lines). The thin gray lines are spin-up lines with $M/M_{\text{Edd}} = 10^{-1}, 10^{-2}, 10^{-3}$ and $10^{-4}$ (top to bottom, and assuming $\sin \alpha = \phi = \omega_c = 1$). In all calculations we assumed a pulsar mass of $1.4 M_\odot$. It is seen how the banana shape of the two fat isochrones (see text) fits very well with the overall distribution of observed pulsars in the Galactic disk. Binary pulsars are marked with solid circles and isolated pulsars are marked with open circles, using data from the ATNF Pulsar Catalogue and corrected for kinematic (Shklovskii) effects. (Fig. adapted from Tauris et al. 2012.)

the diagram over a Hubble time. This trivial fact is important since it tells us that these pulsars were basically born with their currently observed values of $P$ and $\dot{P}$ (first pointed out by Camilo et al. 1994). Hence, some pulsars with characteristic ages of $\tau \approx 100$ Gyr could in principle have been recycled very recently – demonstrating the unreliability of $\tau$ as a true age indicator. It is also interesting to notice PSR J1801$-$3210 (discovered by Bates et al. 2011) which must have been recycled with a relatively slow birth period, $P_0 \sim 7$ ms despite its low $B$-field $< 10^8$ G, see Fig. 1 for its location in the $PP$-diagram.

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A peculiar thermonuclear X-ray burst from the transientsly accreting neutron star
SAX J1810.8–2609

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Abstract. We report on a thermonuclear (type-I) X-ray burst that was detected from the
neutron star low-mass X-ray binary SAX J1810.8–2609 in 2007 with Swift. This event was
longer ($\approx 20$ min) and more energetic (a radiated energy of $E_b \approx 6.5 \times 10^{39}$ erg) than other
X-ray bursts observed from this source. A possible explanation for the peculiar properties is
that the X-ray burst occurred during the early stage of the outburst, when the neutron star
was relatively cold. This allows for the accumulation of a thicker layer of fuel. We also report
on a new accretion outburst of SAX J1810.8–2609 that was observed with MAXI and Swift in
2012. The outburst had a duration of $\approx 17$ days and reached a $2-10$ keV peak luminosity of
$\approx 3 \times 10^{37}$ ($D=5.7$ kpc)$^2$ erg s$^{-1}$. This is a factor $>10$ more luminous than the two previous
outbursts observed from the source, and classifies it as a bright X-ray transient.

Keywords. stars: neutron, X-rays: binaries, X-rays: bursts, X-rays: individual (SAX J1810.8–
2609)

1. Introduction

SAX J1810.8–2609 is a transient neutron star LMXB that was discovered by BeppoSAX on 1998 March 10 when it exhibited an accretion outburst (Ubertini et al. 1998). BeppoSAX and ROSAT observations detected the source at a luminosity of $L_X \approx (0.2 - 1) \times 10^{36}$ ($D/5.7$ kpc)$^2$ erg s$^{-1}$ (2–10 keV), and suggest that the outburst had a duration of $\geq 13$ days (Greiner et al. 1999; Natalucci et al. 2000).

Soon after its discovery, a type-I X-ray burst was detected from SAX J1810.8–2609 (Cocchi et al. 1999; Natalucci et al. 2000). These thermonuclear explosions occur on the surface of accreting neutron stars due to unstable burning of helium/hydrogen. The majority of observed X-ray bursts have a duration of $\approx 10$–100 s and generate a radiated energy output of $E_b \approx 10^{39}$ erg (e.g., Galloway et al. 2008; Chelovekov & Grebenev 2011). Occasionally intermediately-long X-ray bursts are observed, which are more energetic ($E_b \approx 10^{40-41}$ erg) and longer (tens of minutes) than normal X-ray bursts (e.g., in ‘t Zand et al. 2008; Falanga et al. 2008; Linares et al. 2009; Degenaar et al. 2010, 2011).

Renewed activity was detected from SAX J1810.8–2609 with Swift, INTEGRAL and RXTE in 2007 August (Parsons et al. 2007; Degenaar et al. 2007; Haymoz et al. 2007; Fiocchi et al. 2009). During this outburst INTEGRAL detected 17 X-ray bursts, which had an observed duration of $\approx 10$–30 s (3–25 keV; Fiocchi et al. 2009; Chelovekov & Grebenev 2011). The brightest event reached a bolometric peak flux of $F_{\text{peak}} \approx 1 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$, implying a distance of $D \approx 5.7$ kpc (Fiocchi et al. 2009).

† Hubble fellow
2. A long thermonuclear X-ray burst detected with Swift in 2007

On 2007 August 5 at 11:27:26 UT, the Swift/BAT was triggered by SAX J1810.8–2609 (trigger 287042; Parsons et al. 2007). We investigated the trigger data and follow-up XRT observations, and conclude that the BAT triggered on a type-I X-ray burst. For the details on the reduction and analysis procedures we refer to Degenaar et al. (2012a). We carried out exactly the same steps for the analysis of SAX J1810.8–2609.

The BAT light curve shows a single ≃10-s long peak. The average spectrum can be described by a black body model with a temperature of $kT_{bb} \simeq 3.0$ keV and an emitting radius of $R_{bb} \simeq 7$ km (Table 1), which is typical for the peak emission of X-ray bursts. We estimate a bolometric peak flux of $F_{\text{peak}} \simeq 7 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (0.01–100 keV), which is similar to that observed for other X-ray bursts of SAX J1810.8–2609 (Cocchi et al. 1999; Natalucci et al. 2000; Fiocchi et al. 2009; Chelovekov & Grebenev 2011).

Automated follow-up XRT observations commenced ≃65 s after the BAT trigger. The XRT light curve shows a continuous decay in count rate until it settles at a constant level ≃1200 s after the BAT trigger (Figure 1). The light curve can be described by an exponential with a decay time of $\tau \simeq 129$ s, but a power law with a decay index of $\alpha \simeq -1.43$ provides a better fit (Figure 1). The XRT data can be described by a black body model that cools along the decay (Table 1), as is typical for X-ray bursts.

The total estimated fluence of the X-ray burst inferred from the BAT and XRT data is $f_b \simeq 1.6 \times 10^{-6}$ erg cm$^{-2}$. For an assumed distance of $D = 5.7$ kpc, this translates into a total radiated energy of $E_b \simeq 6.5 \times 10^{39}$ erg. We use ≃2 ks of XRT PC mode data obtained between ≃4000–6000 s after the BAT trigger to characterize the persistent accretion emission at the time of the X-ray burst (Figure 1). This data can be described by a simple absorbed power law model with $N_H = (6.2 \pm 0.1) \times 10^{21}$ cm$^{-2}$ and $\Gamma = 2.4 \pm 0.3$. We estimate a bolometric accretion luminosity of $L_{\text{acc}} \simeq 5 \times 10^{35} (D/5.7 \text{kpc})^2$ erg s$^{-1}$. The characteristics of the X-ray burst and persistent emission are summarized in Table 1.

SAX J1810.8–2609 was covered by the RXTE/PCA Galactic bulge scan project between 1999 February 5 and 2011 October 30 (Swank & Markwardt 2001), which reveals one outburst from the source (in 2007). The source was detected above the background level ($L_X \gtrsim 3 \times 10^{35}$ erg s$^{-1}$) between 2007 August 4 and October 28 at an average 2–10 keV luminosity of $L_X \simeq 3 \times 10^{36} (D/5.7 \text{kpc})^2$ erg s$^{-1}$. Non-detections on August 1 and November 1, suggest an outburst duration of ≃85–92 days.
its unusual properties compared to other X-ray bursts observed from the source. This implies that the neutron star crust had likely not yet been significantly heated due to accretion, and hence the heat flux from the crust towards the surface was small. Combined with a low accretion rate ($\dot{m} \approx 0.1 \dot{M}_{\text{Edd}}$), this suggests that the temperature in the accreted envelop was likely low. This allows for the accumulation of a small. Combined with a low accretion rate ($\dot{m} \approx 0.1 \dot{M}_{\text{Edd}}$), this suggests that the temperature in the accreted envelop was likely low.

The X-ray burst from SAX J1810.8–2609 is both longer and more energetic than others observed from the source (Cocchi et al. 1999; Natalucci et al. 2000; Fiocchi et al. 2009; Chelovekov & Grebenev 2011). The duration is similar to that of intermediately long X-ray bursts, but the radiated energy output is an order of magnitude lower. This suggests that the X-ray burst observed from SAX J1810.8–2609 was a normal X-ray burst, albeit with an unusual long duration. There are different explanations for such peculiar X-ray bursts (see Degenaar et al. 2012a, and references therein).

The long X-ray burst of SAX J1810.8–2609 occurred during the early phase of the 2007 outburst. This implies that the neutron star crust had likely not yet been significantly heated due to accretion, and hence the heat flux from the crust towards the surface was small. Combined with a low accretion rate ($\dot{m} \approx 0.1 \dot{M}_{\text{Edd}}$), this suggests that the temperature in the accreted envelop was likely low. This allows for the accumulation of a relatively thick layer of fuel before the ignition conditions are met, and may have caused its unusual properties compared to other X-ray bursts observed from the source.

The X-ray flux observed with MAXI and Swift during the 2012 outburst of SAX J1810.8–2609 is a factor of $>10$ higher than seen during its 1998 and 2007 outbursts. Although the previous activity of the source classified it as a faint LMXB (Natalucci et al. 2000; Jonker et al. 2004; Fiocchi et al. 2009), this demonstrates that it is actually a

### Table 1. Time-resolved spectral analysis of the X-ray burst.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$\Delta t$ (s)</th>
<th>$kT_{bb}$ (keV)</th>
<th>$R_{bb}$ (km)</th>
<th>$F_{bol}$ (erg cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAT</td>
<td>0–10</td>
<td>3.0 $\pm$ 0.5</td>
<td>7.3 $^{+2.9}_{-4.9}$</td>
<td>$4.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>XRT/WT</td>
<td>65–100</td>
<td>1.05 $\pm$ 0.04</td>
<td>8.1 $\pm$ 0.2</td>
<td>$2.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>XRT/WT</td>
<td>101–160</td>
<td>0.90 $\pm$ 0.03</td>
<td>8.0 $\pm$ 0.2</td>
<td>$1.4 \times 10^{-9}$</td>
</tr>
<tr>
<td>XRT/WT</td>
<td>161–265</td>
<td>0.79 $\pm$ 0.03</td>
<td>7.2 $\pm$ 0.2</td>
<td>$6.7 \times 10^{-10}$</td>
</tr>
<tr>
<td>XRT/WT</td>
<td>266–485</td>
<td>0.71 $\pm$ 0.03</td>
<td>6.1 $\pm$ 0.2</td>
<td>$3.1 \times 10^{-10}$</td>
</tr>
<tr>
<td>XRT/PC</td>
<td>492–738</td>
<td>0.69 $\pm$ 0.06</td>
<td>5.1 $\pm$ 0.4</td>
<td>$2.1 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Note. Quoted errors refer to 90% confidence levels. $\Delta t$ indicates the time since the BAT trigger and $F_{bol}$ the estimated bolometric flux over the interval. The simultaneous fit resulted in $N_H = (2.2 \pm 0.3) \times 10^{21}$ cm$^{-2}$ ($\chi^2 = 0.93$ for 281 d.o.f.) and we assumed $D = 5.7$ kpc.

### 3. A new accretion outburst in 2012 seen with MAXI and Swift

MAXI monitoring observations show that SAX J1810.8–2609 was again active between 2012 May 7–24. We estimate an average 2–20 keV luminosity of $L_X \simeq 6.3 \times 10^{36} (D/5.7 \text{ kpc})^2$ erg s$^{-1}$, peaking at $L_X \simeq 2.0 \times 10^{37} (D/5.7 \text{ kpc})^2$ erg s$^{-1}$. The MAXI data suggests that the source intensity was $L_X \gtrsim 10^{36}$ erg s$^{-1}$ for $\approx 17$ days.

A pointed Swift/XRT observation was performed on 2012 May 12 (Obs ID 32459001). The WT spectrum is best described by a combined power law and black body model with $N_H = (0.51 \pm 0.02) \times 10^{21}$ cm$^{-2}$, $\Gamma = 1.67 \pm 0.05$, $kT_{bb} = 0.74 \pm 0.03$ keV, and $R_{bb} = 13.4 \pm 1.4$ km ($\chi^2 = 0.99$ for 721 d.o.f.). The resulting unabsorbed 2–10 keV model flux of $F_X \simeq 6.9 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ implies a luminosity of $L_X \simeq 2.7 \times 10^{37} (D/5.7 \text{ kpc})^2$ erg s$^{-1}$.

Simultaneously obtained UVOT observations using the $uw1$ filter ($\lambda_0 = 2600$ Å) reveal an object at R.A. = 18$^h$10$^m$44.487$^s$, decl. = -26$^\circ$09′01.30″ (with an uncertainty of 0.61″). This coincides exactly with the Chandra position of SAX J1810.8–2609 (Jonker et al. 2004) and suggests that this is the UV counterpart of the LMXB. We determine (Vega) magnitudes of $uw1 = 18.80 \pm 0.12$ and $18.57 \pm 0.22$ mag for the two separate exposures.

### 4. Discussion

The X-ray burst from SAX J1810.8–2609 observed with Swift is both longer and more energetic than others observed from the source (Cocchi et al. 1999; Natalucci et al. 2000; Fiocchi et al. 2009; Chelovekov & Grebenev 2011). The duration is similar to that of intermediately long X-ray bursts, but the radiated energy output is an order of magnitude lower. This suggests that the X-ray burst observed from SAX J1810.8–2609 was a normal X-ray burst, albeit with an unusual long duration. There are different explanations for such peculiar X-ray bursts (see Degenaar et al. 2012a, and references therein).
Table 2. Characteristics of the X-ray burst and the post-burst persistent emission.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolometric accretion luminosity, $L_{acc}$</td>
<td>$\approx 4.9 \times 10^{35}$ erg s$^{-1}$</td>
</tr>
<tr>
<td>Global mass-accretion rate, $\dot{M} = R_{NS} L_{acc}/GM_{NS}$</td>
<td>$\approx 4.1 \times 10^{-11}$ M$_\odot$ yr$^{-1}$</td>
</tr>
<tr>
<td>Local mass-accretion rate, $\dot{m} = \dot{M}/4\pi R_{NS}^2$</td>
<td>$\approx 2.1 \times 10^2$ g cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Bolometric X-ray burst peak flux, $F_{peak}$</td>
<td>$\approx 7 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Exponential decay time, $\tau$</td>
<td>$\approx 129$ s</td>
</tr>
<tr>
<td>Powerlaw decay index, $\alpha$</td>
<td>$\approx 1.43$</td>
</tr>
<tr>
<td>Total duration, $t_b$</td>
<td>$\approx 1200$ s</td>
</tr>
<tr>
<td>Total fluence, $f_b$</td>
<td>$\approx 1.7 \times 10^{-6}$ erg cm$^{-2}$</td>
</tr>
<tr>
<td>Total radiated energy, $E_b$</td>
<td>$\approx 6.5 \times 10^{39}$ erg</td>
</tr>
</tbody>
</table>

Note. The quoted peak flux is unabsorbed and for the 0.01–100 keV energy range. The quoted accretion luminosity and mass-accretion rates were inferred from fitting $\approx 2$ ks of post-burst persistent emission. We assumed a distance of $D = 5.7$ kpc.

bright transient (cf. Wijnands et al. 2006). It is not uncommon for bright X-ray transients to exhibit faint outbursts (e.g., Degenaar & Wijnands 2009; Degenaar et al. 2012b)

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Neutron star masses

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Abstract. Neutron star masses can be inferred from observations of binary pulsar systems, particularly by the measurement of relativistic phenomena within these orbits. The observed distribution of masses can be used to infer or constrain the equation of state for nuclear matter and to study astrophysical processes such as supernovae and binary star evolution. In this talk, I will review our present understanding of the neutron star mass distribution with an emphasis on the observational data.
Constraining neutron star EoS from cooling stages of X-ray bursts

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Abstract. Thermal emission during X-ray bursts is a powerful tool to determine neutron star masses and radii, if the Eddington flux and the apparent radius in the cooling tail can be measured accurately, and distances to the sources are known. We propose here an improved method of determining the basic stellar parameters using the data from the cooling phase of long, photospheric radius expansion bursts covering a large range of luminosities. For this purpose, we computed a large set of atmosphere models for burst luminosities varying by two orders of magnitude and for various chemical compositions and surface gravities. We show that the variation of the inverse square root of the apparent blackbody radius with the flux, observed during the photospheric radius expansion bursts from a number of sources at low accretion rate is entirely consistent with the theoretical expectations of the color-correction factor evolution. However, for bursts happening at higher accretion rates the observed evolution is inconsistent with theory, implying that accretion strongly disturbs the neutron star atmosphere. These findings have profound implications for the recent claims on determination of the neutron star radii and masses from such bursts. Our method allows us to determine both the Eddington flux and the ratio of the stellar apparent radius to the distance much more reliably. For 4U 1724-307, we find a lower limit on the neutron star radius of 13 km, independently of the chemical composition. These results suggest that the matter inside neutron stars is characterized by a stiff equation of state.
Session 6

Neutron star vibration and emission
Merging neutron star binaries: equation of state and electrodynamics

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Abstract. Merging neutron star (NS) binaries may be detected by ground-based gravitational wave (GW) interferometers (e.g. LIGO/VIRGO) within this decade and may also generate electromagnetic radiation detectable by wide-field, fast imaging telescopes that are coming online. The GWs can provide new constraint on the NS equation of state (including mass-radius relation and the related nuclear symmetry energy). This paper reviews various hydrodynamical and electrodynamical processes in coalescing NS binaries, with focus on the pre-merger phase.

Keywords. pulsars – neutron stars – gravitational waves – binaries

1. Introduction

I was asked to talk about thermal radiation from isolated neutron stars (NSs). In this meeting, George Pavlov reviewed the X-ray properties of pulsars and thermally emitting NSs (see Kaplan et al. 2011), and Wynn Ho discussed central compact objects and their magnetic fields (see Halpern & Gotthelf 2010; Shabaltas & Lai 2012; Vigano & Pons 2012). Recent works on theoretical modelling of NS surface emission can be found in Potekhin et al. (2012) (see also Pavlov et al. 1995; Harding & Lai 2006 and van Adelsberg & Lai 2006 for reviews). Since these subjects were adequately covered in the meeting, I decided to focus on a different topic that did not receive much attention in this meeting but is likely to become increasingly important in the coming decade.

Merging NS binaries have been studied since 1970s, with major activities in the relativity community since the early 1990s because of their importance as a source of gravitational waves (GWs) (e.g. Cutler et al. 1993). They are of great current interest for two reasons: (i) Merging NS/NS or NS/Black-Hole (BH) binaries have been identified as the leading candidate for the central engine of short GRBs (Berger 2011). They are also expected to produce optical and radio transients that may be detected by wide-field, fast imaging telescopes that are coming online (e.g. PTF, LSST) in the next few years (Nissanke et al. 2012). (ii) After several decades of promise, gravitational wave astronomy in the Hz-kHz band may finally take off in the next decade. The initial LIGO reached the design sensitivity ($h_c \simeq 10^{-21}$) in 2006, and the enhanced LIGO (with a factor of 2 reduction in $h_c$) is taking or analysing data. The Advanced LIGO and VIRGO are expected to begin observations in 2015 and reach full sensitivity (a factor of 10 reduction in $h_c$) in 2018-19 — at which time the detection of GWs from many merging NS binaries seems guaranteed.

The last three minutes of a NS binary’s life may be divided into two phases: the inspiral phase, producing quasi-periodic GWs, and the coalescence phase, where physical collision results in “messy” GWs. The recent years, 3D simulations of the final merger in full general relativity (GR) have become possible (see Shibata & Taniguchi 2006; Foucart et al. 2012; Sekiguchi et al. 2012). It has long been recognized that the final merger waveforms can provide a useful probe of NS equation of state (EOS; e.g., Cutler
et al. 1993; Bildsten & Cutler 1992; Lai & Wiseman 1996; Wiggins & Lai 2000). The idea is simple: By measuring the “cut-off” frequency \( \propto (GM_t/R_3^3)^{1/2} \) associated with binary contact or tidal disruption, combined with the precise mass measurement from the inspiral waveform, one can obtain the NS radius (recent numerical simulations can be found in Bauswein et al. 2012; Sekiguchi et al. 2012; Faber & Rasio 2012).

In the following sections I will focus on the pre-merger phase.

2. Hydrodynamics of merging NS binaries

Prior to binary merger, tidal effects may affect the orbital decay and the GWs. There are two types of tides: equilibrium tides and dynamical tides. The equilibrium tides correspond to global deformation of the NS, which leads to the interaction potential between the two stars (with the NS mass \( M \) and radius \( R \), the companion mass \( M' \) – treated as a point mass, and the binary separation \( a \))

\[
V(r) = -M M'/a - O \left( k_2 M'^2 R^5/a^6 \right),
\]

where \( k_2 \) is the so-called Love number. This would lead to a correction to the number of GW cycles, \( dN = dN(0) \left[ 1 - O(k_2 M'^2 R^5/a^6) \right] \). For a Newtonian polytropic NS model, simple analytic expressions can be found in Lai et al. (1994). Recent semi-analytic GR calculations of such equilibrium tidal effects (including the more precise determination of the Love number) can be found in numerous papers (e.g., Flanagan & Hinderer 2008; Bin-nington & Poisson 2009; Damour & Nagar 2009; Penner et al. 2012, Ferrari et al. 2012). Obviously this effect is only important at small orbital separations (just prior to merger) – there is some prospect of measuring this, thereby constraining the EOS, but it will be challenging (Damour et al. 2012). More importantly, at small orbital separations, the quadrupole approximation is not valid; there one must use the numerically computed GR quasi-equilibrium binary sequences to characterize the tidal effect – such sequences have been constructed by several groups since the 1990s (e.g., Baumgarte et al. 1998; Uryu et al. 2009).

Another aspect of the equilibrium tide concerns tidal dissipation, which leads to a lag of the tidal bulge with respect to the binary axis. It was shown already in the 1990s (Bildsten & Cutler 1992; Kochanek 1992) that because of the rapid GW-driven orbital decay, viscous tidal lag cannot synchronize the NS spin. Thus the NS will be close to irrotational (approximated as a Riemann-S ellipsoid; Lai et al. 1994; Wiggins & Lai 2000). Near the final phase of the inspiral, the rapid orbital decay gives rise to a finite lag angle (even with zero viscosity), but this cannot synchronize the NS (Lai & Shapiro 1995; Dall'Osso & Rossi 2012).

The situation is more complicated for dynamical tides, which manifest as resonant excitations of internal oscillations of the NS: As two NSs spiral in, the orbit can momentarily come into resonance with the normal modes (frequency \( \omega_\alpha \)) of the NS:

\[
\omega_\alpha = m \Omega_{\text{orb}}, \quad m = 2, 3, \ldots
\]

By drawing energy from the orbital motion and resonantly exciting the modes, the rate of inspiral is modified, giving rise to a phase shift in the gravitational waveform. This problem was studied by Reisenegger & Goldreich (1994), Lai (1994) and Shibata (1994) in the case of non-rotating NSs, where the only modes that can be resonantly excited are g-modes (with typical mode frequencies \( \lesssim 100 \text{ Hz} \)). It was found that the effect is small for typical NS parameters (mass \( M = 1.4 M_\odot \) and radius \( R = 10 \text{ km} \)) because the coupling between the g-mode and the tidal potential is weak. Ho & Lai (1999) studied
the effect of NS rotation, and found that the g-mode resonance can be strongly enhanced even by a modest rotation (e.g., the phase shift in the waveform $\Delta \Phi$ reaches up to 0.1 radian for a spin frequency $\nu_s \lesssim 100$ Hz). They also found that for a rapidly rotating NS ($\nu_s \gtrsim 500$ Hz), f-mode resonance becomes possible (since the inertial-frame f-mode frequency can be significantly reduced by rotation) and produces a large phase shift. In addition, NS rotation gives rise to r-mode resonance whose effect is appreciable only for very rapid (near breakup) rotations. Lai & Wu (2006) further studied resonant excitations of other inertial modes (of which r-mode is a member) and found similar effects. Flanagan & Racine (2006) studied the gravitomagnetic resonant excitation of r-modes and and found that the post-Newtonian effect is more important than the Newtonian tidal effect (and that the phase shift reaches 0.1 radian for $\nu_s \sim 100$ Hz). Tsang et al. (2012) examined crustal modes and found that the GW phase correction is small/modest and suggested that tidal resonance could shatter the NS crust, giving rise to the pre-cursor of short GRBs. Taken together, these studies suggest that for canonical NS parameters ($R \simeq 10$ km, $\nu_s \lesssim 100$ Hz), tidal resonances have a small effect on the gravitational waveform during binary inspiral. However, it is important to remember that the effect is a strong function of $R$ (e.g., $\Delta \Phi \propto R^4$ for g-modes and $\propto R^{3.5}$ for inertial modes). A larger radius ($R \simeq 15$ km) would make the effect important. In the case of g-modes, the magnitude of the effect depends on the symmetry energy of nuclear matter and could be non-negligible (W. Newton & D. Lai 2013, in prep).

3. Electrodynamics of merging NS binaries

For magnetic NSs, magnetic interactions may play a role. If the binary is embedded in a vacuum, then the interaction potential is $V(r) = -M M'/a - O(\mu \mu'/a^3)$ (where $\mu, \mu'$ are the magnetic dipole moments of the two stars). It is easy to check that such magnetic interaction would lead to negligible effect on the GWs unless both NSs have superstrong fields ($\gg 10^{15}$ G) – this is unlikely (e.g., the double pulsars PSR J0737-3039 has $10^{16}$ G for pulsar A and $2 \times 10^{13}$ for pulsar B).

Of course, as in the case of isolated pulsars, the circumbinary environment cannot be vacuum. The following discussion is based on Lai (2012). Consider a binary system consisting of a magnetic NS (the “primary”, with mass $M$, radius $R$, spin $\Omega_s$, and magnetic dipole moment $\mu$) and a non-magnetic companion (mass $M_c$, radius $R_c$). The orbital angular frequency is $\Omega$. The magnetic field strength at the surface of the primary is $B_*=\mu/R^3$. The whole binary system is embedded in a tenuous plasma (magne-
solar flares and accretion disks, have shown that as a flux tube is twisted beyond \( \zeta \approx 1 \), when the twist is too large. (For the Jupiter-Io system parameters adopted by GL, the \( \zeta \approx 1 \).) Thus, a DC circuit with resistances depend on the properties of the binary components and the magnetosphere, and can vary widely for different types of systems. The energy dissipation rate of the system is then \( \dot{E}_{\text{diss}} = 2I^2R_{\text{tot}} = 2\dot{\Omega}^2R_{\text{tot}} \), where the factor of 2 accounts for both the upper and lower sides of the circuit. The total magnetic force (in the azimuthal direction) on the companion is \( \mathbf{F}_{\phi} \approx (2R_c)(2IB_z/c) \), with \( B_z = -\mu/a^2 \). Thus the torque acting on the binary’s orbital angular momentum is \( T = J_{\text{orb}} \approx (4/c)a R_c IB_z \approx -(4\mu R_c/ca^2)(E/R_{\text{tot}}) \). The torque on the primary’s spin is \( J_{\text{rot}} = -T \) (where \( I \) is the moment of inertia). The orbital energy loss rate associated with \( T \) is then \( \dot{E}_{\text{orb}} = T \dot{\Omega} \).

The equations above show that the binary interaction torque and energy dissipation associated with the DC circuit increase with decreasing total resistance \( R_{\text{tot}} \). Is there a problem for the DC model when \( R_{\text{tot}} \) is too small? The answer is yes. The current in the circuit produces a toroidal magnetic field, which has the same magnitude but opposite direction above and below the equatorial plane. The toroidal field just above the companion star (in the upper flux tube) is \( B_{\phi+} \approx -\mu/\Omega_0 \). Thus the azimuthal twist of the flux tube is \( \zeta_{\phi} = -B_{\phi+}/B_z = -16v_{\text{rel}}/(\sqrt{c^2R_{\text{tot}}}) \), where \( v_{\text{rel}} = a\Delta \Omega = a(\Omega - \Omega_c) \). Clearly, when \( R_{\text{tot}} \) is less than \( 16v_{\text{rel}}/c^2 \), the flux tube will be highly twisted. Goldreich & Lynden-Bell (1969) speculated that the DC circuit would break down when the twist is too large. (For the Jupiter-Io system parameters adopted by GL, the twist \( \zeta_{\phi} \ll 1 \).) Since then, numerous works have confirmed that this is indeed the case. Theoretical studies and numerical simulations, usually carried out in the contexts of solar flares and accretion disks, have shown that as a flux tube is twisted beyond \( \zeta_{\phi} \gtrsim 1 \), the magnetic pressure associated with \( B_z \) makes the flux tube expand outward and the magnetic fields open up, allowing the system to reach a lower energy state (e.g., Aly 1985; Aly & Kuijpers 1990; Lynden-Bell & Boily 1994; Lovelace et al. 1995; Uzdensky et al. 2002). Thus, a DC circuit with \( \zeta_{\phi} \gtrsim 1 \) cannot be realized: The flux tube will break up, disconnecting the linkage between the two binary components. A binary system with \( R_{\text{tot}} \lesssim 16v_{\text{rel}}/c^2 \) cannot establish a steady-state DC circuit. The electrodynamics is likely rather complex, only a quasi-cyclic circuit may be possible (Lai 2012): (a) The magnetic field from the primary penetrates part of the companion, establishing magnetic linkage between the two stars; (b) The linked fields are twisted by differential rotation, generating toroidal field from the linked poloidal field; (c) As the toroidal magnetic field becomes comparable to the poloidal field, the fields inflate and the flux tube breaks, disrupting the magnetic linkage; (d) Reconnection between the inflated field lines relaxes the shear and restore the linkage. The whole cycle repeats.

In any case, we can use the dimensionless azimuthal twist \( \zeta_{\phi} \) to parameterize the magnetic torque and energy dissipation rate:

\[
T = \frac{1}{2}\alpha R^2 B_z B_{\phi+} = -\zeta_{\phi} \mu^2 R^2 \frac{\hat{\phi}}{2a^5}, \quad \dot{E}_{\text{diss}} = -T \Delta \Omega = \zeta_{\phi} \Delta \Omega \frac{\mu^2 R^2}{2a^5}. \tag{3.1}
\]

The maximum torque and dissipation are obtained by setting \( \zeta_{\phi} \sim 1 \). If the quasi-
cyclic circuit discussed in the last paragraph is established, we would expect $\zeta_\phi$ to vary between 0 and $\sim 1$. Note that in the above, $T$ is negative since we are assuming $\Omega > \Omega_s$. A reasonable extension would let $\zeta_\phi = |(\Delta \Omega)/\Omega|$, with $\zeta > 0$.

Gravitational wave (GW) emission drives the orbital decay of the NS binary, with timescale $t_{GW} = a/|\dot{a}| = 0.012 (a/30 \text{ km})^4 \text{s}$, where we have adopted $M = 1.4 M_\odot$ and mass ratio $q = M_\nu/M = 1$. The magnetic torque tends to spin up the primary when $\Omega > \Omega_s$. Spin-orbit synchronization is possible only if the synchronization time $t_{\text{syn}} = \Omega_s/T$ is less than $t_{GW}$ at some orbital radii. With $I = \kappa M R^2$, we find

$$t_{\text{syn}} = \frac{2\kappa (1 + q)}{\zeta_\phi \Omega} \left( \frac{GM^2}{B^2 R^4} \right) \left( \frac{a}{R_c} \right)^2 \simeq 2 \times 10^7 \zeta_\phi^{-1} \left( \frac{B_s}{10^{13} \text{ G}} \right)^{-2} \left( \frac{a}{30 \text{ km}} \right)^{7/2} \text{s}, \quad (3.2)$$

where on the right we have adopted $\kappa = 0.4$ and $R = R_c = 10 \text{ km}$. Clearly, even with magnetar-like field strength ($B_s \sim 10^{15} \text{ G}$) and maximum efficiency ($\zeta_\phi \sim 1$), spin-orbit synchronization cannot be achieved by magnetic torque. For the same reason, the effect of magnetic torque on the number of GW cycles during binary inspiral is small.

The energy dissipation rate is

$$\dot{E}_{\text{diss}} = \zeta_\phi \left( \frac{v_{\text{rel}}}{c} \right) \left( \frac{B^2 R^6 R_c^2}{2a^6} \right) = 7.4 \times 10^{44} \zeta_\phi \left( \frac{B_s}{10^{13} \text{ G}} \right)^2 \left( \frac{a}{30 \text{ km}} \right)^{-13/2} \text{erg s}^{-1}, \quad (3.3)$$

where on the right we have used $v_{\text{rel}} \simeq a\Omega$ (for $\Omega_s \ll \Omega$) and adopted canonical parameters ($M = M_\nu = 1.4 M_\odot$, $R = R_c = 10 \text{ km}$). The total energy dissipation per ln $a$ is

$$\frac{d\dot{E}_{\text{diss}}}{d\ln a} = \dot{E}_{\text{diss}} t_{GW} \approx 8.9 \times 10^{42} \zeta_\phi \left( \frac{B_s}{10^{13} \text{ G}} \right)^2 \left( \frac{a}{30 \text{ km}} \right)^{5/2} \text{erg}. \quad (3.4)$$

Some fraction of this dissipation will emerge as electromagnetic radiation counterpart of binary inspiral. It is possible that this radiation is detectable at extragalactic distance. But this will depend on the microphysics in the magnetosphere, including particle acceleration and radiation mechanism (e.g., Vietri 1996; Hansen & Lyutikov 2001).

If one assumes that the magnetosphere resistance is given by the impedance of free space, $R_{\text{mag}} = 4\pi/c$, then the corresponding twist is $\zeta_\phi = 2v_{\text{rel}}/(\pi c)$, which satisfies our upper limit. The energy dissipation rate is then

$$\dot{E}_{\text{diss}} = \left( \frac{v_{\text{rel}}}{c} \right)^2 \left( \frac{B^2 R^6 R_c^2}{\pi a^6} \right) = 1.7 \times 10^{44} \left( \frac{B_s}{10^{13} \text{ G}} \right)^2 \left( \frac{a}{30 \text{ km}} \right)^{-7} \text{erg/s}. \quad (3.5)$$

This is in agreement with the estimate of Lyutikov (2011).

The situation is similar for NS/BH binaries. In the membrane paradigm (Thorne et al. 1986), a BH of mass $M_H$ resembles a sphere of radius $R_c = R_H = 2GM_H/c^2$ (neglecting BH spin) and impedance $R_H = 4\pi/c$. Neglecting the resistances of the magnetosphere and the NS, the azimuthal twist of the flux tube in the DC circuit is $\zeta_\phi = 4v_{\text{rel}}/(\pi c)$, which satisfies our upper limit. The energy dissipation rate is (cf. Lyutikov 2011; McWilliams & Levin 2011)

$$\dot{E}_{\text{diss}} = \left( \frac{v_{\text{rel}}}{c} \right)^2 \left( \frac{2B^2 R^6 R_H^2 c}{\pi a^6} \right) \approx 5.7 \times 10^{42} \left( \frac{B_s}{10^{13} \text{ G}} \right)^2 \left( \frac{M_H}{10 M_\odot} \right)^{-4} \left( \frac{a}{3R_H} \right)^{-7} \text{erg s}^{-1}, \quad (3.6)$$

where we have assumed $M_{BH}/M \gg 1$. Again, it is uncertain whether this radiation can be for binaries at extragalactic distances.

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Quasi-Periodic Oscillations in magnetars: linking variability and emission

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Abstract. I present recent results studying flare emission in magnetars. Strong quasi-periodic oscillations observed in the tail of giant magnetar flares are frequently interpreted as evidence for global seismic oscillations. I demonstrate that such a global oscillation is not directly observable in the lightcurve. New work suggests the amplitude for the strongest QPO stays nearly constant in the rotation phases where it is observed, which I argue suggests it is produced by an additional emission process from the star.

Keywords. dense matter, radiation mechanisms: general, magnetic fields (magnetohydrodynamics:) MHD, stars: neutron, stars: oscillations, X-rays: stars

1. Introduction

In the past few years, considerably theoretical interest has been focused on the seismology of neutron stars (e.g. Levin 2006; Glampedakis et al. 2006; Gabler et al. 2011), largely been motivated by the observation of a series of quasi-periodic oscillations (QPOs) in the decay tails of the giant flares in magnetars SGR 1900+14 and SGR 1806-20 (Israel et al. 2005; Watts & Strohmayer 2006; Strohmayer & Watts 2006). The large amount of energy released during a flare ($\sim 10^{46}$ erg) is likely powered by a global reconfiguration of the star’s magnetic field (Thompson & Duncan 1995) and some of that energy will trigger large-scale quakes in the star (Duncan 1998).

Comparatively little work has been done to connect the putative starquakes directly to the observed QPOs. Timokhin et al. (2008) recently proposed that the oscillations could be attributed to a variable current density in the stellar magnetosphere, created by twisted magnetic field lines anchored in the vibrating star. These electrons then Compton upscatter photons from the surface of the star, modifying the observed spectrum.

In this article I revisit the properties of the QPOs observed in SGR 1806-20 and argue that correlations (or lack thereof) between the variability on different timescales can be used to put strong constraints not only on the QPO origins but also on the emission mechanisms powering the flares themselves.

2. Quasi-Periodic Oscillations in SGR 1806-20

Six distinct QPOs were detected in the SGR 1806-20 giant flare using X-ray data from both the RHESSI and RXTE satellites. The QPOs have central frequencies between 17 and 1837 Hz, with fractional rms amplitudes between 4 and 20%. They are further characterized by a high degree of coherence: of the six detected QPOs, only the one at 150 Hz has a width (full-width at half maximum) of 17 Hz; the others have widths between 1 and 5 Hz (Strohmayer & Watts 2006). There is some evidence for energy dependence in the QPO at 625 Hz, which had an rms amplitude of $\sim 8\%$ below 100 keV, but of rms $\sim 20\%$ between 100-200 keV (Watts & Strohmayer 2006). The energy dependence of
the other QPOs is not clearly detected, but cannot be excluded due to uncertainties in the measured photon energies.

Different QPOs were detected at different time intervals in the decay tail of the flare and at different phases in the rotational pulse profile. The majority of the QPOs were strongest beginning ∼ 200s after the main flare, and in the ‘interpulse’ region in phase, where the flux in the lightcurve is at a minimum (see fig. 1 for the the averaged pulse profile). The strongest QPO in the RXTE data has a central frequency of 93 Hz and fractional rms amplitude of ∼ 20%. It is also detectable over a significant portion of the rotation phase and hence can be used to study the relationship between the QPOs and the pulse profile, as well as relationships between the QPO and broadband noise.

3. Direct detection of a starquake

D’Angelo & Watts (2012) studied whether a starquake could have an observable effect directly on the lightcurve itself by shaking the emitting region. If the pulse profile is very steep (i.e. some component of the pulse is beamed) then the sharp edge of the beam will amplify the underlying motion of the surface, much like a flashlight wiggling in and out of an observer’s line of sight. The change to the rotational phase from the crust motion is given by:

$$\Delta \Phi = \frac{\Delta x}{R_* \sin i \sin \alpha} \sin(2\pi \nu_0 t),$$

(3.1)

where $\frac{\Delta x}{R_*}$ is the fractional amplitude of the starquake, $\nu_0$ is its frequency, and $\sin i$ and $\sin \alpha$ are geometrical factors depending on the beam orientation.

D’Angelo & Watts (2012) found that although significant amplification of a starquake is possible, for the observed lightcurves and realistic, the effect can be excluded. The fractional rms amplitude of a QPO with phase change $\Delta \Phi$ is given by:

$$A \sim \frac{dP}{d\Phi} \frac{\Delta \Phi}{\langle P(\Phi) \rangle},$$

(3.2)

where $P(\Phi)$ is the pulse profile as a function of rotation phase. The amplification provided by a steep gradient is not enough to make a starquake (with $\Delta x/R_* < 0.01$) directly detectable. This result also excludes the possibility that weak, extremely steep ‘pencil beams’ (unresolved in the lightcurve) can provide the amplification. The amplification factor in that case will be given by eq. 3.2 times an additional factor $P_{\text{beam}}/\langle P \rangle$, the fractional amplitude of the steep beam. The beam gradients required in this case are steep enough to be plausibly excluded.

This result strongly suggests the QPOs are produced by variations in the amplitude of the emission itself, rather than the starquake directly.

4. Modulation versus Emission

The physical properties of the QPO can be somewhat constrained from the observed variability of the lightcurve. This is most easily seen from the power spectrum, essentially the squared amplitude of the Fourier transform of a segment of the lightcurve (e.g. van der Klis 1989). The left and right panels of figure 1 show power spectra from the pulsed tail of the giant flare, centered at two different phases of the pulse profile (shown in the bottom panel). In each power spectrum the QPO at 93 Hz is clearly visible, and a fit to the QPO is overlaid. The QPO is significantly narrower in the interpulse region, and the broadband noise (below ∼ 100 Hz) is lower (a second QPO is seen at 30 Hz in the
Figure 1. Power spectrum and pulse profile of the tail of the SGR 1806-20 giant flare for two different segments of the rotational phase (shown by the vertical lines). The QPO at 93 Hz is fit with a Lorentzian distribution (overlaid in red dash-dotted line).

Interpulse spectrum). At the same time, the mean flux in the lightcurve is $\sim 60\%$ lower than in the secondary pulse.

There are two obvious ways that the observed intensity can vary at the QPO frequencies. Either the surface flux can be modulated by a quasi-periodically varying process (like changing optical depth to electron scattering, cf. Timohkin et al. 2008), or the amount of flux being emitted by the star can vary, either through variations in the overall surface emission or via some other instability that produces emission. At present the idea of variable emission in the magnetar magnetosphere is purely speculative, but mechanisms for producing QPOs in solar flares are an active research topic, and some of these could potentially be relevant for magnetar flares as well (see e.g. the review by Nakariakov & Melnikov 2009).

The difference between an emitting process and a modulating one should be observable in the phase-resolved QPOs. A modulating process should produce a correlation between the absolute amplitude of the QPO and the mean flux. In contrast, an emission process should stay constant in phase, and be stronger at phases when the mean flux is lower. Figure 2 shows the fractional change in flux as a function of phase (black line solid), overplotted with the fractional change in QPO amplitude (integrated power over 20Hz centered at 93Hz; red dot-dashed line). As is evident from the figure, the QPO amplitude does not drop as much in the interpulse region, then disappears altogether at the main peak of the burst. The lack of correlation between mean flux and QPO amplitude would suggest that an additional emission process is responsible for its production.

5. Markov Chain Monte Carlo Simulations

Determining the amplitude of the QPOs – particularly those below 100Hz – is complicated by the presence of low-frequency broadband noise (visible in the left panel of fig. 1). Part of the signal at 93 Hz could originate from red noise and not the QPO process, but disentangling the two components is not straightforward (see e.g. Vaughan 2005).

To quantify the uncertainty in QPO amplitude, we use Markov Chain Monte Carlo simulations to generate a series of realizations of a power spectrum with a broadband component and a QPO given by the best fit to the observed spectrum (Vaughan 2010). The variation in the resulting measured parameters can be used to constrain the uncertainty on the QPO fit, and more accurately determine the variation in QPO amplitude as a function of phase. Preliminary results of this analysis suggest that the amplitude
Figure 2. Mean flux (black solid line) and 93Hz QPO amplitude (red dash-dotted line) as a function of phase, for the tail of the SGR 1806-20 giant flare. For the phases where the QPO is detected, the amplitude is consistent with being constant while the mean flux varies substantially.

observed QPO at 93 Hz is consistent with remaining constant over the rotation phase where it is detectable. This would seem to suggest it is independent of the secondary pulse peak, and point to an underlying emission process. The definitive results will be published in a forthcoming paper.

6. Conclusions

The variability of magnetar giant flares on different timescales shows correlations that can constrain the underlying emission mechanism, both for the QPOs and potentially the emission from the giant flares themselves. We have excluded the possibility of directly detecting surface oscillation of the magnetar crust, and have presented preliminary evidence that suggests an additional emission mechanism might be active to produce the quasi-periodic oscillations.

References

Neutron star seismology

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Abstract. I will provide an overview of recent improvements in our models for vibrating neutron stars, discussing the role of composition, heat, crust elasticity and superfluidity. I will explain how the results may impact on observations, in particular related to magnetar QPOs and future gravitational-wave searches.
Magnetar X-ray emission mechanisms

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Abstract. Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are peculiar
X-ray sources which are believed to be magnetars: ultra-magnetized neutron stars which emission
is dominated by surface fields (often in excess of 1E14 G, i.e. well above the QED threshold).

Spectral analysis is an important tool in magnetar astrophysics since it can provide key
information on the emission mechanisms. The first attempts at modelling the persistent (i.e.
outside bursts) soft X-ray (<10 keV) spectra of AXPs proved that a model consisting of a
blackbody (kT 0.3-0.6 keV) plus a power-law (photon index ~2-4) could successfully reproduce
the observed emission. Moreover, INTEGRAL observations have shown that, while in quiescence,
magnetars emit substantial persistent radiation also at higher energies, up to a few hundreds of
keV. However, a convincing physical interpretation of the various spectral components is still
missing.

In this talk I will focus on the interpretation of magnetar spectral properties during quiescence.
I will summarise the present status of the art and the current attempts to model the broadband
persistent emission of magnetars (from IR to hard X-rays) within a self-consistent, physical
scenario.
Long timescale radio emission variability and spin-down changes in PSR J0738-4042

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Abstract. Recently, PSR J0738−4042 has grown a bright new emission component in its average pulse profile. Using data from Parkes and HartRAO, spanning back to the early 1980s, and applying statistical techniques to model the pulse profile shape with time, we have uncovered unexpected long-term variability, which is very well correlated with changes in the spin-down rate. We present these findings in the context of a growing population of radio-variable pulsars with correlated timing irregularities, including the intermittent pulsars, state-changing pulsars and other individual examples.
Session 7

Pulsar timing and

testing gravitational theories
Pulsar Timing Arrays: Status and Techniques

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Abstract. Three pulsar timing arrays are now producing high quality data sets. As reviewed in this paper, these data sets are been processed to 1) develop a pulsar-based time standard, 2) search for errors in the solar system planetary ephemeris and 3) detect gravitational waves. It is expected that the data sets will significantly improve in the near future by combining existing observations and by using new telescopes.

Keywords. gravitational waves, time, ephemerides, pulsars: general

1. Introduction

Pulsar timing data sets are now of sufficient length and precision to start to realise many of the goals of “pulsar timing arrays” (PTAs). The first major PTA was initiated in 2004 using the Parkes radio telescope (Manchester et al., 2012) and is known as the Parkes Pulsar Timing Array (PPTA) project. The European PTA (EPTA) makes use of the telescopes at Jodrell Bank, Westerbork, Effelsberg, Nançay and Sardinia (e.g., Ferdman et al. 2010). The North American PTA (NANOGrav; Jenet et al. 2009) obtains observations using the Arecibo and Green Bank radio telescopes. Together these three PTAs form the International Pulsar Timing Array (IPTA; Hobbs et al. 2010a) which provides high quality timing observations of approximately 40 of the most stable millisecond pulsars known.

The first stage of PTA-related data analyses is to determine the pulse times-of-arrival (ToAs) for each observation of each pulsar. These ToAs are converted from the observatory time standard to a realisation of terrestrial time (TT). Barycentric arrival times are calculated using knowledge of the relative position of the Earth with respect to the solar system barycentre using a planetary ephemeris and by converting from TT to coordinate barycentric time (TCB). These barycentric arrival times are compared with predictions of the arrival times using a model for the pulsar rotational and orbital parameters. The differences between the actual measurements and the predictions are known as the “pulsar timing residuals”. This technique, known as “pulsar timing”, is widely used in pulsar astronomy and is described in detail by Edwards, Hobbs & Manchester (2006).

Various phenomena such as gravitational waves, unexplained timing irregularities, glitch events, errors in terrestrial time standards or in the solar-system ephemeris will induce timing residuals. The main aim of PTAs is to distinguish between these various phenomena by searching for correlations between the timing residuals of multiple pulsars. For instance, pulsar timing irregularities, glitch events or interstellar medium variations will lead to timing residuals that are uncorrelated between different pulsars. In contrast an error in the terrestrial time standard will lead to timing residuals that are identical for different pulsars (assuming that all pulsars have been observed over the same
Figure 1. This figure is reproduced from Hobbs et al., (2012). The top panel shows the sampling for each of the pulsars in our sample. The lower panel shows the difference between the pulsar timescale and TT(TAI) as points with error bars. The solid line indicates the difference between TT(TAI) and TT(BIPM11) after a quadratic polynomial has been fitted and removed. Full details are available in Hobbs et al. (2012).

time span). Errors in the solar-system ephemeris will affect different pulsars depending upon their ecliptic coordinates. The phase and amplitude of timing residuals induced by a gravitational wave will depend upon the pulsar-Earth-source angle (e.g., Detweiler 1979). The expected correlation between different pulsars for timing residuals induced by an isotropic, stochastic gravitational wave background has been calculated by Hellings & Downs (1983).

2. Developing a pulsar time standard

Millisecond pulsar rotation is incredibly stable. This leads to the possibility of developing a time scale based on the pulsar rotation analogous to the free atomic scale, Échelle Atomique Libre (EAL). The Ensemble Pulsar Scale (EPS) can be used to detect fluctuations in atomic timescales and therefore can lead to a new realisation of Terrestrial Time, TT.

Earlier attempts to develop a pulsar timescale have been made by Guinot & Petit (1991), Petit & Tavella (1996), Rodin (2008) and Rodin & Chen (2011). Recently we have developed a method to produce a new time scale based on observations of 19 pulsars obtained for the PPTA project (Hobbs et al. 2012). The new algorithm has been implemented as part of the tempo2 software package (Hobbs, Edwards & Manchester 2006). This algorithm accounts for various features of the observations such as: 1) irregular sampling, 2) different data spans for different pulsars and 3) different fitting parameters for different pulsars. Our result is reproduced in Figure 1. We successfully follow features known to affect the frequency of the International Atomic Timescale (TAI) and we find marginally significant differences between our pulsar time scale, TT(PPTA11), and TT(BIPM11).

This work is being continued by combining the Parkes observations with data from other observatories. The new analysis will confirm or deny the tentative discrepancies
between TT(PPTA11) and TT(BIPM11) whilst significantly improving the stability and precision of the pulsar scale. In the longer term it is expected that a future pulsar time scale will be combined with the best atomic timescale to give the world’s most stable time scale that will be valid effectively forever.

3. Improving the solar system ephemeris

The pulsar timing method relies on the determination of pulse times of arrival as measured in the solar-system barycentre. The procedure requires knowledge of the position of the Earth with respect to the solar-system barycentre. This is obtained using a published solar system ephemeris. Errors in the ephemeris will lead to timing residuals. For instance, an error in the mass of Jovian system assumed when forming the ephemeris will lead to residuals proportional to both the pulsar-barycentre-Jupiter angle and the size of the mass error. As Jupiter orbits the barycentre, the angle will change and hence sinusoidal pulsar timing residuals will be induced with a period equal to that of Jupiter’s orbit.

Champion et al. (2010) searched for such sinusoidal timing residuals using PTA observations of four pulsars obtained using the Arecibo, Parkes and Effelsberg radio telescopes. In most cases published masses obtained from space-craft data were more precise than the pulsar results. However, for the Jovian system, the Champion et al. (2010) measurement of $9.547921(2) \times 10^{-4} M_\odot$ is more accurate than the mass determined from the Pioneer and Voyager space-craft.

The Champion et al. (2010) technique can only be applied to known solar-system objects. However, it is also possible to determine offsets from the predictions of a specific ephemeris in the Earth’s position with respect to the barycentre. Significant offsets in any of the three spatial coordinates can subsequently be analysed in order to identify the orbital parameters of any previously unknown object. In Figure 2 we show the results of an initial analysis using the PPTA observations. We plot the offset in the Earth-barycentre vector as a function of time compared with the value predicted using the JPL
Figure 3. Current upper bounds on the gravitational wave background and past and current predictions. The different symbols are shown in the text.

DE421 Solar System ephemeris. We identify no significant offsets suggesting that the ephemeris is adequate for our current purposes over our five year data span.

The sensitivity of a PTA to errors in the solar system ephemeris depends upon the timing precision achieved and the data span. It is expected that significant improvements will occur when the data span becomes longer than 29 years, the orbital period of Saturn. Combining the observations from the existing timing arrays will also significantly improve our sensitivity.

4. Searching for gravitational waves

Sazhin (1978) and Detweiler (1979) showed that gravitational waves (GWs) passing through the solar system will induce timing residuals that are potentially detectable using PTAs. Pulsar data sets are sensitive to GWs with periods longer than the typical data sampling and shorter than the total time span of the observations. Hence, pulsar experiments are sensitive to ultra-low frequency ($\sim 10^{-9} - 10^{-8}$ Hz) GWs and are complementary to ground-based and space-based GW detectors such as LIGO and eLISA.

Sources of a background of GWs include cosmic strings (see Sanidas et al. 2012, Regimbau et al. 2012 and references therein), the inflationary era (e.g., Zhao 2011) and coalescing supermassive binary black holes (e.g., Sesana, Vecchio & Colacino 2008). The induced timing residuals induced by a GW background is often described as having a red power spectrum:

$$P(f) = \frac{A^2}{12\pi^2} \left(\frac{f}{f_{\text{1yr}}}\right)^{2\alpha_{GW}-3}.$$ (4.1)

The almost horizontal lines in Figure 3 show recent upper bounds that have been placed on $A(\alpha)$ by Jenet et al., (2006), Van Haasteren et al. (2011) and Demorest et al. (2012). For comparison an earlier upper bound by Kaspi, Taylor & Ryba (1994) is plotted as a downward pointing arrow.

Since the start of the PPTA project our expectations for the detectable GW signal have
changed. In Figure 3 we show the past and current predictions for the signal strength and spectral exponent. Estimates that were available at the time that our first upper bound was published (Jenet et al. 2006) for cosmic strings, the inflationary era and black holes are shown as the left-most vertical solid line, the hollow rectangle and the right-most vertical solid line respectively. Since 2006, new research has (1) broadened the possible range of $\alpha_{GW}$ and indicated that very few constraints are available on the lower amplitude of the cosmic-string background signal (Sanidas, Battye & Stappers 2012; shown as the left-most hashed region in Figure 3), (2) confirmed that the most-likely signal from the inflationary era has a very low amplitude (the small hashed region near the bottom-centre of the figure should be considered as an upper-bound on the amplitude of this signal) and 3) led to the possibility that the background caused by coalescing black holes is flatter than originally predicted (right-most hashed region).

Earlier work has assumed that the detected GW signal will be an isotropic, stochastic background. More recent studies have suggested that the exact nature of the detected signal could be a background, but may be an individual non-evolving source, a chirping system, a memory event, or a burst event. Various algorithms have therefore been developed to search for these various signals (e.g., Yardley et al. 2010; Finn & Lommen 2010; Cordes & Jenet 2012).

5. Improving the data sets

The sensitivity of a PTA data set to a given science goal depends upon the timing precision achieved, the noise present in the data, the number of pulsars observed and the data span. For most millisecond pulsars over decadal time scales the dominant noise source is caused by turbulence in the interstellar medium leading to variations in the pulsar’s dispersion measure (e.g., You et al. 2007). This effect can only be removed by observing the pulsar at widely separated observing frequencies. To help address this problem many PTAs are now developing wide-band receiver systems that provide a large frequency coverage for each observation.

For many pulsars, the dominant uncorrectable noise is caused by receiver noise and pulse jitter. Receiver noise can only be reduced using more sensitive telescopes or longer observations. In the future it is expected that telescopes such as the Five-hundred metre spherical telescope (FAST) in China, or the Square Kilometre Array (SKA) will provide a huge increase in sensitivity. However, individual pulse-shape variations or jitter may provide a limit to the precision with which pulse arrival times can be measured and therefore require a modified strategy in the use of these new telescopes (Oslowski et al. 2011, Liu et al. 2012).

Over long time scales pulsars are known to exhibit irregularities in their spin-down rate (e.g. Verbiest et al. 2009 and Hobbs et al. 2010b). It is currently thought that this noise is uncorrectable and will limit the stability of pulsars over long time scales. However, recent work (Lyne et al. 2011) has shown that it may be possible to identify a deterministic component to these irregularities which opens up the possibility of at least partially correcting for their effects. In any case, the discovery of new, stable pulsars is necessary to improve the sensitivity of the PTA projects. Numerous surveys are ongoing (e.g., Cordes et al. 2006, Keith et al. 2010, Boyles et al. 2012) and are leading to the discovery of a large number of new, millisecond pulsars. Including these new pulsars in existing PTAs and the likelihood of a large number of new, sensitive radio telescopes in the relatively near future suggest that the future is bright for PTA research.
6. Acknowledgements

We acknowledge the dedication and skills of the engineers and support staff at the various observatories without whom the various Pulsar Timing Array projects could not exist. GH thanks A. Sesana, S. Sanidas and X. Siemens for interesting discussions on the parameters of the expected gravitational wave background and R. Manchester, W. Coles and J. Verbiest for comments on the manuscript.

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Prospects for probing strong gravity with a pulsar-black hole system

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Abstract. The discovery of a pulsar (PSR) in orbit around a black hole (BH) is expected to provide a superb new probe of relativistic gravity and BH properties. Apart from a precise mass measurement for the BH, one could expect a clean verification of the dragging of space-time caused by the BH spin. In order to measure the quadrupole moment of the BH for testing the no-hair theorem of general relativity (GR), one has to hope for a sufficiently massive BH. In this respect, a PSR orbiting the super-massive BH in the center of our Galaxy would be the ultimate laboratory for gravity tests with PSRs. But even for gravity theories that predict the same properties for BHs as GR, a PSR-BH system would constitute an excellent test system, due to the high grade of asymmetry in the strong field properties of these two components. Here we highlight some of the potential gravity tests that one could expect from different PSR-BH systems, utilizing present and future radio telescopes, like FAST and SKA.

Keywords. pulsars: general, black hole physics, relativity

In the following we summarize the work presented in Liu et al. (2012), Liu (2012) and Liu et al. (in prep.). Based on these publications, we will highlight three different aspects of testing gravity with a PSR-BH system:

- Testing gravity with a PSR in orbit with a stellar mass ($\sim 10M_\odot$) BH.
- Testing gravity with a PSR in orbit around the BH in the Galactic center, Sgr A$^*$.
- Testing scalar-tensor gravity with a PSR-BH system, as an example for the probing power of a PSR-BH system for gravity theories, in which BHs are the same as in GR.

The results given are based on extensive mock data simulations and consistent timing models, which are explained in detail in Wex & Kopeikin, Liu et al. (2012), and Liu (2012). Furthermore, these simulations have been conducted for three different types of radio telescopes: a 100-m class telescope, FAST and SKA. A detailed discussion on the expected timing precision for these telescopes can be found in Liu et al. (2012) and Liu (2012).

\[†\] Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
1. Black hole properties

One of the most intriguing results of general relativity (GR) is the uniqueness theorem for the stationary BH solutions of the Einstein-Maxwell equations (see Chruściel et al. 2012, and references therein). It implies that in GR all uncharged BH solutions are described by the Kerr metric and, therefore, uniquely determined by mass $M$ and spin $S$. Astrophysical BHs are believed to be the result of a gravitational collapse, during which all the properties of the progenitor, apart from mass and spin, are radiated away by gravitational radiation (Price 1972a,b). The outer spacetime of an astrophysical BH should therefore (to a very good approximation) be described by the Kerr metric. Since the Kerr metric has a maximum spin at which it still exhibits an event horizon, Penrose’s cosmic censorship conjecture (CCC) within GR (Penrose 1979) requires the dimensionless spin parameter $\chi$ to satisfy

$$\chi \equiv \frac{c}{G} \frac{S}{M^2} \leq 1 \quad (1.1)$$

A measured value for $\chi$ that exceeds 1 would pose a serious problem for our understanding of spacetime, since this would indicate that either GR is wrong or that a region may be visible to the outside universe, where our present understanding of gravity and spacetime breaks down.

As a result of the no-hair theorem, all higher multipole moments ($l \geq 2$) of the gravitational field of an astrophysical BH can be expressed as a function of $M$ and $S$ (Hansen 1974). In particular, the dimensionless quadrupole moment $q$ satisfies the relation

$$q \equiv \frac{c^4}{G^2} \frac{Q}{M^3} = -\chi^2. \quad (1.2)$$

A measurement of the quadrupole moment, in combination with a mass and a spin measurement, would therefore identify the BH as a Kerr BH and provide a test of the no-hair theorem for BHs.

2. A pulsar in orbit with a stellar-mass black hole

Concerning possible formation scenarios of PSR-BH systems, a detailed discussion is presented in Liu (2012) and Liu et al. (in prep.). For the following, it is only important to notice that there are several formation scenarios that lead to a PSR-BH system with a recycled PSR.

2.1. Mass determination

The most precise mass measurements for stars (other than the Sun) come from PSR timing observations (Lorimer & Kramer 2005, Weisberg et al. 2010). Those are achieved in binary PSR systems, where in addition to the Keplerian parameters one can determine a set of post-Keplerian (PK) parameters that describe the relativistic correction in the orbital motion and signal propagation. In GR (and many alternative theories of gravity) the PK parameters are functions of the Keplerian parameters and the two a priori unknown masses of the system, which can be determined once two PK parameters have been obtained (Lorimer & Kramer 2005). In a PSR-BH system the observation of PK parameters will allow the determination of the BH mass with unprecedented precision. Fig. 1 (taken from Liu et al., in prep.) illustrates the precision that one can expect with a 100-m class telescope. Future telescopes like FAST and SKA would yield a significantly higher precision, as demonstrated by the simulations in Liu (2012) and Liu et al. (in prep.).
Figure 1. Fractional error for different PK parameters, which can be used to determine the mass of the BH, as a function of the orbital period. The figure is based on mock data simulations for weekly observations over 5 years with a 100-m class telescope, assuming a recycled PSR in a mildly eccentric ($e = 0.1$) orbit with a $10 M_\odot$ BH. Note that $\dot{\omega}$ is expected to have a significant contribution from the frame-dragging caused by the rotation of the BH, and can a priori not be used in the mass determination. For a comparison, the three stars mark the precision obtained in the Hulse-Taylor pulsar (top to bottom: $\dot{P}_b$, $\gamma$, $\dot{\omega}$; Weisberg et al. 2010).

2.2. Frame dragging

It has been shown by Wex & Kopeikin that the Lense-Thirring precession of the orbit, caused by the relativistic spin-orbit coupling, between the orbital angular momentum and the BH spin, is the best way to measure the magnitude and direction of the BH spin. Once the second time derivatives of the longitude of periastron and the projected semi-major axis become observable in the timing data, the spin can be determined. Fig. 2 (taken from Liu et al., in prep.) illustrates the precision that one can expect with SKA. A spin measurement in a PSR-BH system would verify the frame dragging caused by a rotating BH, and test the CCC inequality $\chi \leq 1$.

Figure 2. Fractional error in the BH spin, as a function of the orbital period. The figure is based on mock data simulations for weekly observations over 5 years with SKA, assuming a recycled PSR in a mildly eccentric ($e = 0.1$) orbit. $m_c$ denotes the BH mass.
2.3. Quadrupole moment

In order to perform a test of the no-hair theorem, it would be necessary to measure the quadrupole moment of the BH. As already argued by Wex & Kopeikin, such a measurement has to be based on the periodic features in the orbital motion, caused by the unique structure of the gravitational potential associated with the quadrupole moment. Our simulations, presented in Liu (2012) and Liu et al. (in prep.) show, that only for a very massive BH ($\gtrsim 30 M_\odot$) and very tight orbits ($P_b \lesssim 0.2 \text{ d}$) one can hope to measure the quadrupole signature in the data, provided one has the superb timing precision of the SKA. We consider it as not very likely, that such a system can be found in nature, in particular since such a system would have a very short lifetime in the order of a few Myr.

3. A pulsar in orbit around Sgr A*

According to the previous section, a system consisting of a radio PSR and a stellar mass BH will most likely not allow the determination of the BH quadrupole moment to test the no-hair theorem. Since the quadrupole moment becomes more important for more massive BHs, one wishes to find a PSR in orbit around the most massive BH in our Galaxy, Sgr A* in the Galactic center ($M \sim 4 \times 10^6 M_\odot$; Ghez et al. 2008, Gillessen et al. 2009). Finding and timing a PSR in orbit around Sgr A* comes with certain challenges, which are discussed in more details in Liu et al. (2012), Eatough et al. (this proceedings) and references therein. In short, it is more likely to detect a young PSR with a rotational period $\sim 0.5 \text{ s}$, which then would give us a timing precision in the order of $\sim 0.1 \text{ to } 1 \text{ ms}$. All this requires observational frequencies $\gtrsim 20 \text{ GHz}$. Furthermore, one would also have to worry about perturbations by other masses in the immediate vicinity of Sgr A* (see Liu et al. 2012, and references therein). In the results presented here we assume a clean orbit and a weekly time-of-arrival measurement with 0.1 ms uncertainty. As we will see, this is already sufficient, to go all the way to the no-hair theorem test, i.e measuring the mass $M$, spin $S$ and quadrupole moment $Q$ of Sgr A* with sufficient precision.

3.1. Mass determination and the distance to the Galactic center

For the precision that can be obtained in determining the mass of Sgr A* from PK parameters, the PSR can be seen as a test mass in orbit around Sgr A*. In this case the measurement of one PK parameter is sufficient. A fractional precision of $10^{-5}$, or even better, should be easily possible with a PSR in a $\lesssim 1 \text{ yr}$ orbit (Liu et al. 2012). Such a precision is not only key to extract the Lense-Thirring contribution to the peri-center precession $\dot{\omega}$, it would also allow, in combination with astrometric observations of the S-stars, to determine the distance to the Galactic center $R_0$, since, unlike the astrometric mass, the mass measurement from PSR timing is not affected by an uncertainty in $R_0$.

3.2. Frame dragging

Although there is clear indication that Sgr A* rotates, its actual rate of rotation is still not well determined, and a rather large range in the estimates of $\chi$ can be found in the literature (see references in Liu et al. 2012), which is a result of the uncertainty in the underlying model assumptions. A PSR would, in the absence of any major external perturbations, give direct access to the dragging of inertial frames in the vicinity of Sgr A*. Like in the case of stellar mass BHs, the (additional) precession of a PSR orbit due to the

† According to our estimates, in combination with a 10 $\mu$as infrared astrometry, an uncertainty of just a few pc could be reached.
frame dragging (Lense–Thirring precession) is the most promising effect to determine the direction and magnitude of the BH spin. Liu et al. (2012) have used extensive mock data simulations to show, that for orbits below an orbital period of 0.5 years, where external perturbations are likely to be negligible, the spin parameter $\chi$ could be measured with a precision of $10^{-4}$ to $10^{-3}$, or even better in case of very short orbital periods ($P_b \lesssim 0.1$ yr) and/or high eccentricities ($e \gtrsim 0.8$). This would be a test of the frame dragging caused by a super-massive BH and, like in section 2.2, a test of the CCC inequality $\chi \lesssim 1$.

3.3. No-hair theorem test

For a BH, with a given spin parameter $\chi$, the quadrupole moment grows very fast with increasing mass ($\propto M^3$). For this reason, even for rather wide orbits of several 10 AU the quadrupole moment of Sgr A* is expected to give rise to measurable effects in the orbital motion. The calculations in Liu et al. (2012) clearly show, that the observable amplitudes of the “quadrupole effect”, for an orbit of a few 0.1 yr, are of order of several milli-seconds, and should allow a better than 1% test of the no-hair theorem. In contrast to an astrometric no-hair theorem test (Will 2008), only one star (here the PSR) is needed and the orbital eccentricity can be considerably less extreme (see Fig. 10 in Liu et al. 2012).

4. Scalar-tensor gravity and PSR-BH systems

In the previous sections we have seen the potential to probe the properties of gravity with a PSR in orbit around a BH. But even for gravity theories that predict the same properties for a BH as GR, a PSR-BH system would be an excellent probe, that can be superior to all present binary PSR experiments. An important class of gravity theories where this is the case, as pointed out by Damour & Esposito-Farèse (1998), are scalar-tensor theories. Scalar-tensor gravity, in which gravity is mediated by a tensor field $g_{\mu \nu}^*$ and by a massless scalar field $\varphi$, are well motivated and physically consistent alternatives to GR, that have been studied extensively (see Fujii & Maeda 2003). In the scalar-tensor gravity, investigated in detail in Damour & Esposito-Farèse (1996), the orbital motion of a binary system depends, besides the Einstein masses $m_A, m_B$ on the effective coupling constants $\alpha_a = \partial \ln m_a / \partial \varphi_0$ ($a = A, B$), and their scalar-field derivatives $\partial \beta_a / \partial \varphi_0$, where $\varphi_0$ denotes the asymptotic value of $\varphi$ at spatial infinity. In a PSR-BH system, we have $\alpha_{BH} = 0$ (and consequently $\beta_{BH} = 0$) because of the no-scalar-hair theorems, which considerably simplifies the equations for the PK parameters given in Damour & Esposito-Farèse (1996). Of particular interest here is the leading term in the gravitational wave damping (dipolar radiation) of the orbital period $P_b$, that is simply

$$\dot{P}_b^{\text{dipolar}} \simeq -\frac{4\pi^2G}{c^5P_b} \frac{m_{\text{PSR}} m_{\text{BH}}}{m_{\text{PSR}} + m_{\text{BH}}} \frac{1 + e^2/2}{(1 - e^2)^{3/2}} \alpha_{\text{PSR}}^2. \quad (4.1)$$

For a given equation-of-state, the effective scalar coupling of the PSR, $\alpha_{\text{PSR}}$, depends on the two fundamental coupling parameters of the theory, $\alpha_0$ (linear) and $\beta_0$ (quadratic), and the mass of the PSR, which we assume to be the canonical value of $1.4 M_\odot$. Liu et al. (in prep.) have conducted extensive mock data simulations for different types of telescopes and different orbital parameters to demonstrate the superb capabilities of a PSR-BH binary to constrain scalar-tensor gravity. Figure 3 presents some of these results. As can be seen there, in particular with future radio telescopes a PSR-BH system would provide an extremely sensitive test for the presence of a scalar degree of freedom in the gravitational interaction.
Figure 3. Constraints in the $\beta_0$–$\alpha_0$ plane (different PSRs and a hypothetical PSR-BH system). Details are given in Freire et al. (2012) and Liu et al. (in prep.). Limits by a hypothetical PSR-BH system, consisting of a recycled PSR in orbit with a $10 \, M_\odot$ BH ($P_b = 5 \, \text{d}$, $e = 0.8$) are given by dashed lines, which exclude the region above and left of them. The three lines, correspond to (top to bottom): 10 yr weekly timing with a 100-m class telescope, 5 yr weekly timing with FAST, and 5 yr weekly timing with SKA.

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Constraining the nanohertz gravitational wave background with the Parkes Pulsar Timing Array

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Abstract. The direct detection of gravitational waves will usher in a new era of astrophysics, enabling the study of regions of the universe opaque to electromagnetic radiation or electromagnetically quiet. An ensemble of pulsars (referred to as a pulsar timing array) provides a set of clocks distributed across the Galaxy sensitive to gravitational waves with periods on the order of five years (frequencies of many nanohertz). Plausible source of gravitational waves in this frequency band include massive black hole binaries in the throes of mergers and oscillating cosmic strings. The stochastic gravitational wave background, the sum of gravitational waves emitted throughout the universe, is the most likely signal to be detected by a pulsar timing array.

While the detection of gravitational waves will be a milestone in pulsar astronomy, a constraining limit on the strength of the gravitational wave background can be used to constrain cosmological models and early Universe physics. Here we present a new algorithm that can be used to constrain the strength of the GWB with a pulsar timing array. We then apply this technique to Parkes Pulsar Timing Array observations and place a new limit on the strength of the GWB. We conclude by discussing the astrophysical implications of this limit and the prospects for detecting gravitational waves with pulsars.
Stochastic and continuous gravitational wave
analysis pipelines for pulsar timing array
data

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Abstract. The Nanohertz Observatory for Gravitational Waves (NANOGrav) collaboration aims to detect gravitational waves (GWs) through the precise timing of millisecond pulsars. GWs will come in the form of a stochastic background, continuous sources and burst sources. Here we will review recent progress on the development of data analysis pipelines aimed at the detection of a stochastic background as well as continuous sources. We will introduce the Optimal Statistic and F-Statistic methods that are used in the stochastic and continuous pipelines, respectively. Both pipelines are fully functional on real pulsar timing data and take into account the timing models for each pulsar. Finally, we will present the efficacy of each pipeline on locally simulated data as well as data from the 2012 IPTA data challenge.
19 Years of high precision timing of the millisecond pulsar J1713+0747

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Abstract. We report the analysis of a 19-year span of timing data on PSR J1713+0747 taken by the Arecibo and Green Bank telescopes. PSR J1713+0747 is one of the best high-precision pulsars monitored by the NANOGrav project for the purpose of detecting gravitational waves. The timing precision of this pulsar can be regarded as the benchmark of NANOGrav timing instruments. We show the precision improvement achieved by multi-generation instruments including the Green Bank Ultimate Pulsar Processing Instrument (GUPPI) and its counterpart in Arecibo. The new timing solution we found improves the measurement of the pulsars mass, its orbital and geometric parameters, sets new limits on alternative gravitational theories, and may provide a high-quality single pulsar gravitational wave upper limit.
Update on the European Pulsar Timing Array

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Abstract. The European Pulsar Timing Array (EPTA) is one of the three global Pulsar Timing Array communities, aiming to use the clock nature of pulsars to detect gravitational wave. In this talk, I will provide an introduction to the current status of EPTA pulsar observations and present an overview of the recent results. I will also give an update on the progress of the Large European Array for Pulsar (LEAP) project, which attempts to coherently combine the data from the five biggest single site radio telescopes in Europe and make an equivalently 200-metre diameter dish. The LEAP project is an ideal effort in performing high precision pulsar timing and studying characteristics of single pulses from millisecond pulsars.
Session 8

Pulsar Timing
Timing noise and the long-term stability of pulsar profiles

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Abstract. It has recently been shown that there is a close correlation between the slowdown rates and the pulse shapes of six pulsars, and between the slowdown rates and the flux density of three others. This indicates that these phenomena are related by changes in the current flows in the pulsar magnetospheres. In this paper we review the observational status of these studies, which have now been extended to a total of 16 pulsars having correlated slowdown and pulse emission properties. The changes seem to be due to sudden switching between just two discrete magnetospheric states in the well-known processes of mode-changing and pulse nulling. We also address how widespread these phenomena are in the wider pulsar population.

1. Introduction

Timing noise is low-frequency fluctuation in the rotation-rate of pulsars and is evident in the timing residuals of all young and middle-aged pulsars. The basic properties of timing noise were reviewed recently by Hobbs et al. (2010) who presented the results of an analysis of the rotation of 366 pulsars. In summary, timing noise is seen as smooth changes in the timing residuals (and rotation frequency). The timing residuals are often asymmetric, with peaks and troughs having different radii of curvature; the variations are often quasi-periodic with timescales which are typically 1-10 years. For long, it was thought to arise from the fluid interiors of the neutron stars.

A breakthrough was made in 2006, when Kramer et al. showed that the timing noise in the long-term intermittent pulsar B1931+24 could be explained in detail by switching in the magnitude of the slowdown rate $\dot{\nu}$ between the "ON" and "OFF" emission states of the pulsar, indicating that changes in the current flow from the pulsar resulted in changes of both the radio emission and of the braking torque. The implication that changes in magnetospheric currents could alter pulsar emission properties as well as slowdown rate led Lyne et al. (2010) (hereafter LHKSS) to study the detailed pulse profiles of some of those pulsars having the largest amounts of timing noise. They demonstrated that six of these pulsars exhibited the well-known phenomenon of mode-changing, in which a pulsar switches abruptly between two stable profiles. Moreover, in all six pulsars, there was a high degree of correlation between the pulse shape and slowdown rate, the pulsars switching rapidly between low- and high-spindown rates.

Two years after the publication of LHKSS, we review the observational evidence for switched changes in magnetospheric states, both in intermittent pulsars and in mode-changing pulsars, and discuss the relationship between the two phenomena.

2. Intermittent pulsars

Many pulsars show intermittency in their radio emission, although usually the durations of the "ON" and "OFF" states are measured in seconds to hundreds of seconds,
Figure 1. The rotational frequency evolution of PSR J1832+0029 (Lorimer et al. 2012).

Figure 2. The rotational frequency evolution of PSR J1841−0500 (Camilo et al. 2012 and Lyne, priv. comm.).

timescales which are far too short to permit the determination of any change in slowdown rate between the states. This is the phenomenon of pulse nulling which has been known since shortly after the discovery of pulsars (Backer 1970).

However, the intermittent pulsar B1931+24 is typically ON for 1 week and OFF for about 1 month, permitting Kramer et al. (2006) to show that the ratio of ON- and OFF- slowdown values $\dot{\nu}_{\text{ON}}/\dot{\nu}_{\text{OFF}} = 1.5 \pm 0.1$, roughly consistent with an absence of all magnetospheric currents during the OFF phase, in accordance with the calculations of the braking effects of magnetospheric currents by Goldreich & Julian (1969).

Shortly after that publication, a second long-term intermittent pulsar was discovered (PSR J1832+0029) and reported to show similar large changes in in slowdown rate ($\dot{\nu}_{\text{ON}}/\dot{\nu}_{\text{OFF}} = 1.7 \pm 0.1$; Kramer 2008, Lyne 2009, Lorimer et al. 2012). Fig. 1 shows the measured values of rotation rate during the 10 years since its discovery. With rather poor statistics, the lengths of the ON and OFF states are typically many hundreds of days, compared with tens of days for B1931+24.

More recently, a third long-term intermittent object (PSR J1841−0500), also with
timescales measured in hundreds of days, has been reported by Camilo et al. (2012).
Even though the statistics are also poor for this pulsar, it is clear that this has an even
greater slowdown rate ratio ($\dot{\nu}_{ON}/\dot{\nu}_{OFF} = 2.5 \pm 0.2$; see Fig. 2).

3. Profile-switching pulsars

LHKSS studied those pulsars in the Jodrell Bank timing database which showed the
largest amounts of timing noise, measured as the ratio of maximum to minimum values
of slowdown rate. Seventeen examples are shown in Fig. 3. Pulsars typically have peak-
to-peak values of about 1% of the mean, over a 4-orders-of-magnitude range of slowdown
rates. Individual pulsars may have a factor of 10 times more or less than this. LHKSS
found that six of the 17 pulsars showed pulse-shape changes which were correlated with
these slowdown rate variations. Subsequent studies (Lyne et al., in prep) have now shown
that a further four of these 17 also have significant pulse-shape variations that are cor-
related with slowdown rate (PSRs B0919+06, B1642−03, B1826−17 and B1903+07) as
well as two others (PSRs B1740−03 and B0105+65).

A further striking example of correlated changes in pulse shape and slowdown is dis-
played by PSR J2047+5029, discovered at Westerbork in the 8gr8 survey (Janssen et al.
2009). At discovery, the observed profile showed a main pulse and an interpulse with an
associated precursor having about 1/3 of the flux density of the main pulse (Fig. 4 top).
However, when monitoring commenced at Jodrell Bank, the main pulse had reduced in
intensity by a factor of about 10, so that it was then much weaker than the interpulse
(Fig. 4 bottom). The pulsar has since changed from this “abnormal mode” back to the
earlier “normal” mode. These changes were accompanied by changes in slowdown rate,
which was larger when in the normal mode than in the abnormal mode, again consistent
with the notion that the particles responsible for much of the normal-mode main-pulse
radio flux density were also responsible for the increase in braking.

**Figure 3.** The slowdown rate ($\dot{\nu}$) of 17 pulsars (from Lyne et al. 2010).
Figure 4. The profiles of the “normal” (top) and “abnormal” (bottom) states of PSR J2047+5029 (Janssen et al., in prep.).

Table 1. Timing noise slowdown rate ratios ($\dot{\nu}_1/\dot{\nu}_2$) and emission changes in 16 pulsars.

<table>
<thead>
<tr>
<th>PULSAR</th>
<th>$\dot{\nu}_1/\dot{\nu}_2$</th>
<th>Emission Change</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1841−0500</td>
<td>2.5</td>
<td>Deep null</td>
<td>Camilo et al. (2012)</td>
</tr>
<tr>
<td>J1832+0029</td>
<td>1.7</td>
<td>Deep null</td>
<td>Lorimer et al. (2012)</td>
</tr>
<tr>
<td>B1931+24</td>
<td>1.5</td>
<td>Deep null</td>
<td>Kramer et al. (2012)</td>
</tr>
<tr>
<td>B2035+36</td>
<td>1.13</td>
<td>20% change in $W_{50}$</td>
<td>Lyne et al. (2010)</td>
</tr>
<tr>
<td>B1740−03</td>
<td>1.13</td>
<td>70% change in component ratio</td>
<td>This paper</td>
</tr>
<tr>
<td>B0105+65</td>
<td>1.11</td>
<td>30% change in $W_{50}$</td>
<td>This paper</td>
</tr>
<tr>
<td>B1903+07</td>
<td>1.07</td>
<td>10% change in $W_{50}$</td>
<td>This paper</td>
</tr>
<tr>
<td>J2043+2740</td>
<td>1.06</td>
<td>100% change in $W_{50}$</td>
<td>Lyne et al. (2010)</td>
</tr>
<tr>
<td>B1822−09</td>
<td>1.033</td>
<td>100% change in precursor/interpulse</td>
<td>Lyne et al. (2010)</td>
</tr>
<tr>
<td>J2047+5029</td>
<td>1.030</td>
<td>90% change in main pulse</td>
<td>Janssen et al. (in prep)</td>
</tr>
<tr>
<td>B1642−03</td>
<td>1.025</td>
<td>20% change in cone/core</td>
<td>This paper</td>
</tr>
<tr>
<td>B1540−06</td>
<td>1.017</td>
<td>12% change in $W_{10}$</td>
<td>Lyne et al. (2010)</td>
</tr>
<tr>
<td>B1828−11</td>
<td>1.007</td>
<td>100% change in $W_{10}$</td>
<td>Lyne et al. (2010)</td>
</tr>
<tr>
<td>B1826−17</td>
<td>1.007</td>
<td>10% change in cone/core</td>
<td>This paper</td>
</tr>
<tr>
<td>B0919+06</td>
<td>1.007</td>
<td>30% change in component ratio</td>
<td>This paper</td>
</tr>
<tr>
<td>B0740−28</td>
<td>1.007</td>
<td>20% change in $W_{75}$</td>
<td>Lyne et al. (2010)</td>
</tr>
</tbody>
</table>

In total there are now 16 pulsars with established synchronised changes in the radio emission and the slowdown rate. The properties of these pulsars are summarised in Table 1, in decreasing order of the magnitude of the timing noise, measured as the ratio of the maximum and minimum slowdown rates.

4. The nature of the switching

The time sequences of slowdown rates shown in Fig. 2 are usually bounded by well-defined maximum and minimum levels, each extreme level being identifiable with a characteristic emission profile or flux density. As reported by LHKSS, each pulsar is usually seen to switch abruptly between these extreme states. The fact that the patterns in Fig. 2 are generally smooth and do not display abrupt switching behaviour was demonstrated to arise from changing statistical properties of the mode-changing phenomenon, and the observed profile shape parameter is determined by the proportion of time spent in the two modes. This is most clearly illustrated in Fig. 5 which shows a number of 8-hour observations of PSR B1828−11 chosen at different phases of the 500-day oscillating pat-
Figure 5. Four 8-hour time-sequences of the profile state of PSR B1828−11, taken at four different phases of the 500-day oscillation seen in Fig. 3 for this pulsar. Although the switching timescale may be short, the fraction of time spent in one state or the other changes slowly (Stairs et al. in prep.)

tern displayed by this pulsar in Fig. 3. We note that although pulse nulling and profile mode-changing was first observed in 1970 (Backer 1970; Backer 1970a), the following four decades have seen no study of the stability of the statistics of nulling or mode-changing.

5. The relationship between nulling and mode-changing

The processes of nulling and mode-changing are similar in many ways. Both are switched phenomena between (usually) two discrete emission states. They both have similar large ranges of timescales and both have a major synchronisation with the spin-down rate of the pulsar. They are both understood in terms of changes in magnetospheric particle currents. The natural conclusion is that nulling is probably an extreme form of mode-changing. This view is supported by a few cases in which an apparently nulling pulsar has been found to have low-level emission in the null state. One such example is PSR B0826−34 shown in Fig. 6, in which integration of the data during apparently “null” episodes shows pulsed emission at a level of about 2% of the un-nulled pulses.

Perhaps one telescope’s nulling pulsar is a larger telescope’s mode-changing pulsar !

6. Conclusions

Pulsar magnetospheres switch between a small number of discrete states, usually two, each of which corresponds to an apparently quasi-stable magnetospheric configuration. It seems that changes in magnetospheric current flows between these states cause variations in both the emission beam and the slow-down rate. This is supported by the general observation that the larger slowdown-rate is nearly always associated with enhanced emission, particularly of the pulsar “core” emission. I have no understanding of why there are these discrete states, or of the origin of the multi-year quasi-periodicities that modulate the statistical properties of the states. Free-precession of the neutron star and orbiting asteroids have been proposed, but any links are obscure.

Finally, it must be emphasised that these phenomena are widespread. The majority of
pulsars of young and intermediate characteristic age display detectable timing noise. The studies of profiles described here have mostly been of those pulsars which have the largest fractional changes in slowdown rates and hence may be expected to suffer the greatest magnetospheric changes and corresponding variation in emission properties. In fact, 12 of the 19 pulsars with largest timing noise show correlated emission variations. Most of the remaining 7 have much poorer signal-to-noise ratio, making the precise determination of pulse shape changes challenging. The changes expected in less timing-noisy pulsars are likely to be much more subtle and a challenge to detect. At present, there is no reason to doubt that all timing noise has its origin in switched magnetospheric states.

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Testing gravity theories in the radiative regime using pulsar timing arrays

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Abstract.
General relativity has predicted the existence of gravitational waves (GW), which are waves of the distortions of space-time with two degrees of polarization and the propagation speed of light. Alternative theories predict more polarizations, up to a maximum of six, and possible frequency dependent propagation speed from the light speed. The polarization and dispersion properties of GWs shed light on the spin and mass information of gravitons. Although GWs have not been directly detected yet, their amplitude upper-bounds has been addressed by research using different types of detectors. For example, the amplitude upper-bounds for the stochastic background derived from pulsar timing observations have already become astrophysically interesting. The present paper reviews proposals to test the gravity theories in the radiation regime by observing GWs using pulsar timing arrays. We also present the estimation for the upper-bounds on the amplitude of alternative modes for the stochastic background of GW.

Keywords. gravitational waves, (stars:) pulsars: general, elementary particles

1. Introduction
Two major characteristics of GWs are important to differentiate the validity of gravity theories in the radiative regime; the polarization and dispersion of GW in vacuum. In alternative metric theories, GW can have up to six possible polarization states, four more than which are allowed by GR. Furthermore, the propagation speed of GW can deviate from the predication of GR that GW propagates at light speed in vacuum, i.e. the effective graviton mass is zero.

A pulsar timing array is a unique technique to detect nano-Hertz GWs by timing multiple millisecond pulsars, which are very stable celestial clocks (Jenet et al. 2005). It turns out that a stochastic GW background leaves an angular-dependent correlation in pulsar timing residuals for widely spaced pulsars (Hellings & Downs, 1983): the correlation $C(\theta)$ between timing residual of pulsar pairs is a function of angular separation $\theta$ between the pulsars. One can analyse the timing residual and measure such a correlation to detect GWs (Jenet et al. 2005). Lee et al. (2008, 2010) have found that the exact form of $C(\theta)$ is very different from the one of GR, if the GW has extra polarization state or graviton mass is not zero. By measuring the correlation function, we can directly test gravity theories in the radiative regime.

2. Pulsar timing correlation functions and gravity tests
A GW introduces extra signal in pulsar timing data. Let the unit vector of the GW propagation direction be $\hat{e}_z$, GW frequency be $f$, the direction from the observer to the photon source (pulsar) be $\hat{n}$. The GW induced frequency-shift of a pulsar timing signal
\[ \frac{\Delta \omega(t)}{\omega} = \frac{\hat{n} \cdot \hat{n}'}{2\left(1 + \frac{\omega}{2\pi f} k_g \cdot \hat{n}\right)} \left[h_{ij}(t, 0) - h_{ij}(t - |D|/c, D)\right], \quad (2.1) \]

where the $D$ is the displacement vector from the observer to the pulsar, $h_{ij}(t, 0)$ and $h_{ij}(t - |D|/c, D)$ are the metric perturbations by GW at the Earth and at the pulsar when the received pulse was emitted, $\omega$ is the angular frequency for the pulsar pulse, $f_{\text{cut}} = m_g c^2 / h$ is the cut-off frequency of GW due to the graviton mass $m_g$, and the $k_g$ is the GW wave vector given by Lee et al. (2010)

\[ k_g(f) = \frac{2\pi}{c} \left(f^2 - f_{\text{cut}}^2\right)^{\frac{1}{2}} \hat{e}_z. \quad (2.2) \]

The induced pulsar timing residuals $R(t)$ are given by the temporal integration of above the frequency shift at Earth given above, thus

\[ R(t) = \int_0^t \frac{\Delta \omega(\tau)}{\omega} d\tau. \]

The spatial metric perturbation $h_{ij}(t, r)$ induced by a stochastic GW background is a superposition of monochromatic GWs with random phases and amplitudes. It is (Maggiore, 2000)

\[ h_{ij}(t, r) = \sum_{P=+,\times} \int_{-\infty}^{\infty} df \int d\Omega h_P(f, \hat{e}_z) \epsilon_P^{ij}(\hat{e}_z) e^{i[2\pi ft - k_g f(r)]}, \quad (2.3) \]

where $\Omega$ is the solid angle, index $i,j$ run from 1 to 3, $h_P$ is the amplitude of the GW propagating in the direction of $\hat{e}_z$ per unit solid angle per frequency of polarization state $P$, and the polarization tensor $\epsilon_P^{ab}$ of GWs are given in details in Lee et al. (2008). The superscript $P$ takes value of ‘+$, ‘×’ for the two Einsteinian modes of GW polarization, ‘b’ and ‘l’ for the breathing and the longitudinal mode respectively, and ‘sn, se’ for the shear modes.

Such stochastic GW background leaves a correlation between timing residuals of pulsars pairs. Such correlation, $C(\theta)$, depends on the angular distance $\theta$ between two pulsars as well as on the polarization of GW and graviton mass.

Lee et al. (2008) have calculated the pulsar timing correlation function for all the polarization modes of GW. For the Einsteinian modes and for the breathing mode, the cross-correlation function $C_P(\theta)$ is independent of earth-pulsar distances and independent of the GW characteristic strain spectrum. In contrast, for the modes that are not purely transverse, the shear and longitudinal modes, the cross correlation functions depend on the specifics of the strain spectra and on the pulsar distribution in distance.

Fig. 1 shows the correlation function according to different classes of GW polarization. Clearly by comparison of these ‘theoretical’ correlation curves with observations we can test the polarization state of GWs.

Lee et al. (2010) have calculated the pulsar timing correlation function for a GW background with none-zero-mass graviton. They noted that the pulsar timing cross-correlation function for a massive GW background depends on the graviton mass, specific power spectra of the GW background, and on the observation schedule. The 5-year and 10-year correlation functions are reproduced in Fig. 2, where the graviton with the same mass introduces more deviation to the 10-year correlation function than it does to the 5-year one.

Intuitively speaking, the necessary conditions for a positive detection of a graviton mass should be: 1. The GW is strong enough such that the GW can be detected; 2. the physical effects of alternative theories should be strong enough to see the deviation from
Figure 1. The normalized pulsar timing residual correlation coefficients. Here $\theta$ is the angular separation between two pulsars. ‘GR’ stands for the two transverse traceless modes, ‘+’ and ‘×’. Results are given for several values of $\alpha$, the power-law index of the GW spectrum.

Figure 2. The atlas for cross-correlation functions $C(\theta)$. The label of each curve indicates the corresponding graviton mass in unit of electron-volts (eV). The left panel are the correlation functions for a 5-year bi-weekly observations. The right panel shows correlation functions for 10-year bi-weekly cases. We take $\alpha = -2/3$ for these results. These correlation are normalized such that the $C(0) = 0.5$ for two different pulsars.

GR. These intuition is confirmed by simulations in, which show that the high detection rate is achieved only if one has enough pulsar and if the graviton mass is large enough or if GW of alternative polarization modes is strong enough.

For identifying the polarization modes, observation shows that if bi-weekly observations are made for five years with RMS timing accuracy of 100 ns, then 60 pulsars are required for the longitudinal mode; 60 for the two spin-1 “shear” modes; and 40 for the spin 0 “breathing” mode and 40 pulsars are needed for the detection of the GR modes.

For detecting massive graviton, simulations have shown that we need at least 60 pulsars to be able to tell the difference between a massive GW background and a massless one. For 5-year timing of 100 pulsar we can start to detect a graviton heavier than $2.5 \times 10^{-22}$
eV and we can achieve a limit of \( m_\gamma = 10^{-22} \) eV by using 5-year observation of 300 pulsars. We can achieve levels of \( 10^{-22} \) eV and \( 5 \times 10^{-23} \) eV in a 10-year observation using 100 and 300 pulsars respectively.

3. Estimation for the upper-bounds on the amplitude of the alternative modes

The power spectra \( S(f) \) of the timing residual is defined as \( S(f) = 2 \int_{-\infty}^{\infty} dt e^{-2\pi if(t)} \langle R(t)R(t+t) \rangle \), with \( f \geq 0 \). Assuming an power-law spectra for the stochastic background of GW, i.e. characteristic strain \( h_c \equiv A_c (f/f_c)^\alpha \), one can show that

\[
S_R^{+\times}(f) = \frac{A_c^2 f^{2\alpha-3}}{24\pi^2 f_c^{2\alpha}}
\]

\[
S_R^b(f) = \frac{A_c^2 f^{2\alpha-3}}{12\pi^2 f_c^{2\alpha}}
\]

\[
S_R^{\text{sn},se}(f) = \frac{A_c^2 (3\ln(4\pi f_D/c) + 3\gamma_e - 7) f^{2\alpha-3}}{24\pi^2 f_c^{2\alpha}}
\]

\[
S_R^l(f) = \frac{A_c^2 D f^{2\alpha-2}}{16\pi f_c^{2\alpha}}
\]

where the \( D \) is the distance of the pulsar, \( \gamma_e \approx 0.58 \) is the Euler’s \( \gamma \) constant. The superscripts take the same meaning as in the polarization index ‘\( P \)’ in the \( h^P \). One can see that the power spectrum of the longitudinal mode and shear modes are proportional to the distance of pulsar \( D \) and its logarithm \( \ln D \) respectively. The physical reasons for the phenomena is that the GWs of the two modes and pulsar signals traveled and kept the phases along the similar path, in this way, the pulsar signals could accumulate the GW effects. Recently, this has also been noted by Alves & Tinto (2011) and Chamberlin & Siemens (2012).

These formulae can be used to “estimate” the upper-bounds for the alternative modes by converting the results from upper-bounds for the GR modes. From Equations(3.1), we can see that the spectra of the timing residuals are all power-law like for power-law GW background. In this way, we can translate the upper-bounds as function of power index \( \alpha \) for GR modes to the alternative modes as

\[
A_{up}^{(b)}(\alpha) = A_{up}^{(GR)}(\alpha)
\]

\[
A_{up}^{(\text{shear})}(\alpha) = \frac{A_{up}^{(GR)}(\alpha)}{\sqrt{3\ln(4\pi f_0 D/c) + 3\gamma_e - 7}}
\]

\[
A_{up}^{(l)}(\alpha) = \frac{A_{up}^{(GR)}(\alpha + \frac{1}{2})}{\pi} \frac{4c}{\sqrt{3D f_c}}
\]

Using the upper bounds derive by Jenet et al. (2006), we can estimate the upper bounds for alternative modes, as given in the Figure. (3)

4. Conclusion and Discussion

The stochastic GW background produces extra timing signals in pulsar TOA data, and one can detect the GW background by precise timing several pulsars and measuring the angular dependent correlations between the timing signals of several pulsars. A precise measurement of the angular correlation function can, in principle, determine the GW
polarization properties of the GWs making up the stochastic background as well as the graviton mass. A large number of pulsars with good timing precise of \( \sim 100 \) ns are required to successfully perform tests for gravity theories in radiative regime. In this regard, pulsars surveys’ success in finding more millisecond pulsars is critical. To time such large number of pulsars, the Large European Array for Pulsars (Stappers, Vlemmings, & Kramer, 2009), the Five-hundred-meter Aperture Spherical Radio Telescope (Nan et al., 2006, Smits et al., 2009) and the Square Kilometer Array (SKA) will offer unique opportunities to detect the GW background and measure its properties.

5. Acknowledgment

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References


The spin evolution of young pulsars

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Abstract. The current understanding of the spin evolution of young pulsars is reviewed through a compilation of braking index measurements. An immediate conclusion is that the spin evolution of all pulsars with a measured braking index is not purely caused by a constant magnetic dipole. The case of PSR J1734-3333 and its upward movement towards the magnetars is used as a guide to try to understand why pulsars evolve with \( n < 3 \). Evolution between different pulsar families, driven by the emergence of a hidden internal magnetic field, appears as one possible picture.

Keywords. pulsars: general, pulsars: individual (PSR J1734–3333), stars: neutron.

The spin frequency \( (\nu) \) of all pulsars is observed to decrease and the rate of this spin-down \( (\dot{\nu}) \) is commonly related to the magnitude \( B \) of a dipolar magnetic field rotating with the star. The spin-down of pulsars can be characterised by the braking index \( n \), which is defined via \( \dot{\nu} \propto \nu^n \) and, provided we are able to detect the long-term second time-derivative of the spin frequency \( \ddot{\nu} \), it can be measured by

\[
    n = \frac{\ddot{\nu}}{\dot{\nu}^2} .
\]

Another way to visualise the spin evolution of pulsars is by using a period–period-time-derivative plot with all known pulsars (the \( P\dot{P} \) diagram, Fig. 2). As their periods increase, pulsars move to the right in this diagram, with a slope \( 2 - n \) determined by the dominant braking mechanism in operation. In particular, for braking due to a constant magnetic dipole we expect \( n = 3 \) and pulsars to move to the right and downward with a slope of \(-1\). To date, the few measurements available indicate \( n < 3 \) (i.e. slope \(< -1\)).

Commonly, the age of a pulsar is assumed to be equal to the so-called characteristic age, \( \tau_c = \nu/2\dot{\nu} \), under the assumption that the pulsar evolved with a constant \( n = 3 \) and that the initial spin frequency was significantly larger than the current value. We know that young pulsars evolve with \( n < 3 \), hence \( \tau_c \) is a poor age estimator. More braking index measurements and a better understanding of the spin-down physics are essential to track the rotational history of pulsars and estimate their real ages.

The \( P\dot{P} \) diagram is populated by various families of pulsars which exhibit different emission or rotational properties and/or are found in different astrophysical contexts, like binary systems, supernova remnants, etc. (cf. Kaspi 2010). A better understanding of the movement of pulsars on the diagram will offer insights on the possible relationship between these families (Kaspi 2010; Espinoza et al. 2011), which is essential to understand the Galactic population of neutron stars (Keane & Kramer 2008).

1. PSR J1734–3333

PSR J1734–3333 is a radio pulsar rotating with a period \( P = 1.169 \) s and with a rather high period derivative \( \dot{P} = 2.3 \times 10^{-12} \) implying \( B = 5 \times 10^{13} \) G (Morris et al. 2002), a value comparable to the inferred magnetic field of some magnetars (Fig. 2). There are
no glitches detected for this pulsar and its levels of timing noise are relatively low. By using 13.5 years of data from the Jodrell Bank Observatory and the Parkes telescope, Espinoza et al. (2011) measured \( \dot{\nu} \) for this pulsar and calculated \( n = 0.9 \pm 0.2 \). Therefore, the spin-down of PSR J1734–3333 is not purely caused by a constant dipole magnetic field. Its movement in the \( P-\dot{P} \) diagram is upwards and with a slope of at least 0.9. If the physics responsible for this evolution remains the same, PSR J1734–3333 will be located among the magnetars, with a period of 8 s, in less than 30 kyr (Espinoza et al. 2011).

2. Other braking index measurements

Braking index measurements have been possible only for a few pulsars. The main difficulty is found on the detection of the secular \( \ddot{\nu} \) caused by the spin-down mechanism. The effects of \( \ddot{\nu} \) in the data, in addition to be very small, are obscured by the effects of glitches and timing noise. In this section we collect most \( n \) measurements dividing the sample of pulsars in two main groups, according to their spin-down behaviour.

2.1. The case of very young pulsars

Very young pulsars have \( \tau_c \) values around 1 kyr and are associated to supernova remnants of similar ages. They present rather linear \( \dot{\nu} \) time-evolutions and the secular \( \ddot{\nu} \) is easy to detect via coherent timing or by just measuring the slope of the \( \dot{\nu} \) curve. Glitches in these pulsars appear not to have a dramatic effect on the long-term linear behaviour of \( \dot{\nu} \) (see, for example, the left panel in Fig. 1 and the \( \dot{\nu} \) evolution of PSR J1119–6127 in Fig. 10 of Weltevrede et al. (2011)). The braking index measurements for these pulsars have all been performed via coherent timing and can be found on the left part of Table 1. We include in this group a recent measurement for PSR J1833–1034.

2.2. The case of Vela-like pulsars

The braking index of the Vela pulsar (PSR B0833–45) was measured by Lyne et al. (1996) using a particular method to overcome the presence of large glitches. Other pulsars with similar rotational properties to the Vela pulsar also exhibit large glitches of comparable size, occurring at semi-regular time intervals. It is this regularity what allowed Lyne et al. (1996) to track the long-term \( \dot{\nu} \)-evolution of the Vela pulsar and measure \( \dot{\nu} \). We have updated the method and studied the \( \dot{\nu} \) evolution of the Vela pulsar (now including 14 glitches) and the three Vela-like pulsars PSRs B1757–24, B1800–21 and B1823–13 (Espinoza et al. 2012). As preliminary results, here we report rather low braking indices for all these four pulsars (Table 1). Table 1 also includes a braking index for PSR

![Figure 1](image-url). The \( \dot{\nu} \) time-evolution of the Crab pulsar (PSR B0531+21) over more than 40 yr (left) and of PSR B1800–21 over about 25 yr (right). Glitches appear as negative jumps.
Table 1. Measured braking indices.

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>n</th>
<th>Ref.</th>
<th>Pulsar</th>
<th>n</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0531+21</td>
<td>2.51(1)</td>
<td>Lyne et al. (1993)</td>
<td>J0537−6910</td>
<td>1.5</td>
<td>Middleditch et al. (2006)</td>
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<tr>
<td>B0540−69</td>
<td>2.140(9)</td>
<td>Livingstone et al. (2007)</td>
<td>B0833−45</td>
<td>1.7</td>
<td>Espinoza et al. (2012)</td>
</tr>
<tr>
<td>J1119−6127</td>
<td>2.91(5)</td>
<td>Weltevrede et al. (2011)</td>
<td>J1734−3333</td>
<td>0.9(2)</td>
<td>Espinoza et al. (2011)</td>
</tr>
<tr>
<td>B1509−58</td>
<td>2.839(1)</td>
<td>Livingstone et al. (2007)</td>
<td>J1747−2958</td>
<td>&lt; 1.3</td>
<td>Hales et al. (2009)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B1824−13</td>
<td>2</td>
<td>Espinoza et al. (2012)</td>
</tr>
</tbody>
</table>

J0537−6910, based on a rough $\dot{\nu}$ estimate performed over $\dot{\nu}$ data including a number of large glitches and an upper limit for PSR J1744−2958.

3. Discussion and questions for the future

All 13 pulsars in Table 1 exhibit $n < 3$. This result implies that the spin-down of young pulsars is not driven by an electromagnetic torque caused by a constant magnetic dipole. Either the dipole is changing with time, the braking is produced by higher order multipoles or there are other processes that efficiently compete with the electromagnetic torque, like stellar winds, other magnetospheric processes or internal processes related to superfluid dynamics (Blandford & Romani 1988; Michel 1969; Li et al. 2012; Ho & Andersson 2012).

The low $n$ of PSR J1734−3333 has been attributed to an increase of the dipole component of its magnetic field (Espinoza et al. 2011). Simulations show that the dipole’s magnitude could increase as a result of the re-emergence of a stronger magnetic field.

Figure 2. The $P-\dot{P}$ diagram for pulsars with $\dot{P} > 1.65 \times 10^{-15}$. Arrows indicating the position after one $\tau_c$ are plotted for the pulsars in Table 1. Thick, closed arrows are for Vela-like pulsars, the open arrow is for PSR J1734−3333 and the thin arrows are for the very young pulsars. Constant $B$ lines are segmented and constant $\tau_c$ lines are dotted.
buried by hypercritical accretion occurred immediately after the supernova explosion (Muslimov & Page 1996; Viganò & Pons 2012). If this is a common situation among young pulsars, different strengths and submergence conditions of the internal magnetic field, together with different initial periods, could produce the low braking indices measured on young pulsars, the properties of CCOs (Ho 2011; Viganò & Pons 2012) and also offer a new genesis for the magnetars (Lyne 2004; Espinoza et al. 2011). In this picture, CCOs, young radio pulsars and magnetars are all one single family, conveniently reducing the total number of neutron stars in the Galaxy (c.f. Keane & Kramer 2008).

We acknowledge, however, that the actual situation might be more complicated because the spin-down of pulsars is probably the result of a superposition of various processes. The values in Table 1 are represented in the $P-\dot{P}$ diagram in Fig. 2 by arrows, which indicate the position pulsars will have after one $\tau_{\dot{P}}$. In general, very young pulsars have negative slopes and Vela-like pulsars and PSR J1734-3333 have positive slopes. Are the pulsars in these two groups irreconcilably different? Or, will very young pulsars evolve into Vela-like pulsars? What sort of processes could produce this transformation?

It is practically impossible to discriminate from timing data which is the exact spin-down mechanism operating on a given pulsar. Hence, it is unclear whether the spin evolution of very young pulsars is caused by the same process as the other pulsars or not. In the future, it will be important to study the efficiency of the different braking mechanisms and understand how they compete with each other; what kind of observable signatures we might expect from each of them and how they evolve as pulsars age.

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† Excepting PSR J0537−6910, for which only 2,000 yr were used.
PSR J1906+0746: From relativistic spin-precession to beam modeling

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Abstract.
Shortly after the discovery of PSR J1906+0746, some hints of profile variations were already interpreted as first signs of relativistic spin-precession occuring. Using observations from the Nançay, Arecibo and Green Bank Radio Observatories, we report here the measurement of pulse profile and polarimetric variations. Using the Rotating Vector Model, we show that PSR J1906+0746 is likely to be an orthogonal rotator (α ≃ 80°). Fitting our polarimetric data to a precession model, we determined the geometry of the pulsar and found a wide misalignment angle (δ = 89° ± 44°, 95% C.L.), although the uncertainty is large. Assuming this geometry, we constructed the beam maps of both magnetic poles.

Keywords. pulsars: individual (J1906+0746)

1. Introduction
PSR J1906+0746 is a young pulsar in a 4-hr orbit around a massive companion (Lorimer et al. 2006). With a pulsar mass \( M_p = 1.323 \pm 0.011 M_\odot \) and a companion mass \( M_c = 1.290 \pm 0.011 M_\odot \) derived from timing measurement by Keane et al. (2012), one can estimate the relativistic spin-precession period to be 165 years assuming General Relativity.

Relativistic spin-precession in binary pulsars is a long-known effect that is due to spin-orbit coupling (Damour & Ruffini 1974; Barker & O’Connell 1975). The consequence of this precession is that our line of sight crosses different parts of the radio beam with time. Hence we can expect pulse shape and polarization variations.

The non-detection of the interpulse in archival data and an increase of the signal-to-noise ratio (SNR) for the main pulse between 1998 and 2005, suggested the first sign of change in the beam orientation with respect to our line of sight (Lorimer et al. 2006). Profile shape variations were also reported by Kasian (2008) when they presented their timing solution. More recently, they reported a preliminary beam map for the main pulse (Kasian 2012).
Figure 1. Mean pulse profile of PSR J1906+0746 as recorded in 2005 with the NRT.

We present in these proceedings further observations that allow us to determine the geometry of the pulsar and produce improved maps of its radio beam.

2. Observations

This pulsar was observed from 2005 to 2009 with the BON backend at the Nançay Radio Telescope (hereafter NRT; Desvignes 2009) and the WAPPs, ASP and GASP backends at the Arecibo 305-m Observatory and the Green Bank Telescope respectively (for further details, see Kasian 2012). All these observations were done at L-Band. Only the NRT observations provide calibrated full Stokes profiles that were de-Faradayed with a Rotation Measure of $149 \text{ rad m}^{-2}$ and hence were used for the polarimetric study. Given the low SNR of the NRT daily observations, the NRT profiles were integrated to form 13 profiles spanning 3 to 6 months to obtain reliable polarimetric fits.

3. Profiles and polarimetric changes

The mean pulse profile at the beginning of our dataset in 2005 consists of 2 sharp pulses separated by almost 180° (see Fig. 1). Over the 3 years course of the data span, we measured a change in the separation of the two pulses to be $2.1^\circ \pm 0.1^\circ \text{ yr}^{-1}$.

The flux density of both components was also estimated for each dataset using the radiometer equation, e.g. Lorimer & Kramer (2005). It decreased by a factor of $\sim 3$ and $\sim 4.5$ for the main pulse and the interpulse respectively.

Our polarization data first confirmed the high degree of linear polarization noticed in the discovery paper (Lorimer et al. 2006). However, the circular polarization under the main pulse gradually vanished between our first and last epochs. According to the Rotating Vector Model (RVM) put forward by Radhakrishnan & Cooke (1969), the typical ‘S’ curve of the Polarization Position Angle (PPA) can be described in terms of the geometry of the pulsar:

$$\tan(\psi - \psi_0) = \frac{\sin \alpha \sin(\phi - \phi_0)}{\sin(\alpha + \beta) \cos \alpha - \cos(\alpha + \beta) \sin \alpha \cos(\phi - \phi_0)},$$

(3.1)

where $\alpha$ is the angle between the rotation and magnetic axis and $\beta$ denotes the impact
impact parameter as a function of MJD. The black boxes show the impact parameter as determined by the simple RVM fits. The black line represents the model from the best fit values given by Table 1. The inset shows a zoom over the data.

Figure 2. Impact parameter $\beta$ as a function of MJD. The black boxes show the impact parameter as determined by the simple RVM fits. The black line represents the model from the best fit values given by Table 1. The inset shows a zoom over the data.

parameter. Here $\psi$ is the measured PPA at the longitude $\phi$, $\phi_0$ the longitude under the magnetic axis at the closest approach of the line of sight and $\psi_0$ the PPA at the longitude $\phi_0$.

Fitting the RVM to each of our 13 polarimetric profiles, we measured $\alpha$ to be close to 80° for all epochs. A constant value of $\alpha$ is expected and this result strongly suggests an orthogonal rotator, with the two pulses representing the cone of emission of both magnetic poles. The RVM results also show a small increase of $\beta$ with time (i.e. the slope of the PPA under the main pulse in decreasing with time), indicating that our line of sight is moving away from the magnetic poles. More importantly, a marginal decrease of $\psi_0$ is also detected.

In the next section, we used this change in $\psi_0$ to determine the geometry of the system and map the radio emission beams.

4. Modeling of relativistic spin precession

Kaplan et al. (2009) have shown that the absolute value of the PPA $\psi_0$ should change with time. Applying their global precession model and fitting for the magnetic inclination angle $\alpha$, the misalignment angle $\delta$, the reference precessional phase $\Phi_{SO}$ plus the 13 phase offsets give the results reported in Table 1.

The magnetic inclination angle is consistent with the value determined with the simple RVM fit. The large value of the misalignment angle explains our quick detection of the precession effects. Its large uncertainty can be justified by the fact that the impact parameter did not have a sign reversal as it happened for PSR J1141–6545 (Manchester et al. 2010).

With the geometry of the system derived, we can now produce a map of the emission

Table 1. Results of the global precession model at a 95% confidence level.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\delta$</th>
<th>$\Phi_{SO}$</th>
<th>$\chi^2_{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>81$^{+1}_{-66}$</td>
<td>89$^{+8}_{-44}$</td>
<td>83$^{+11}_{-41}$</td>
<td>2.22</td>
</tr>
</tbody>
</table>
beam. First, a set of gaussians is fitted to all profiles. The height of the gaussians are normalized using flux density measurements.

When producing the beam map for PSR J1141−6545, Manchester et al. (2010) aligned the pulse profiles using the edges. In this work, the profiles are aligned with respect to the magnetic poles based on the individual measurements of \( \phi_0 \) given by the simple RVM fits, hence making no assumption on the beam shape. This alignment based on polarimetric results explains the offset in the main pulse longitude between this beam map and the one produced by Keane et al. (2012).

The results of the beam maps are shown Fig. 3. In the case of the main pulse, we see axial emission with the flux decreasing as the line of sight is moving away from the magnetic pole. For the interpulse, the emission is more extended.

The beam maps clearly show the change in the separation of the two components as the line of sight is moving away from the magnetic poles. These profile variations will undoubtedly have an impact on the timing study of this pulsar (van Leeuwen et al., in prep.) beyond the usual timing noise in young pulsars (Lyne et al. 2010).

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The superslow pulsation X-ray pulsars in high mass X-ray binaries

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Abstract. There exists a special class of X-ray pulsars that exhibit very slow pulsation of \( P_{\text{spin}} > 1000 \) s in the high mass X-ray binaries (HMXBs). We have studied the temporal and spectral properties of these superslow pulsation neutron star binaries in hard X-ray bands with INTEGRAL observations. Long-term monitoring observations find spin period evolution of two sources: spin-down trend for 4U 2206+54 (\( P_{\text{spin}} \sim 5560 \) s with \( \dot{P}_{\text{spin}} \sim 4.9 \times 10^{-7} \) s s\(^{-1}\)) and long-term spin-up trend for 2S 0114+65 (\( P_{\text{spin}} \sim 9600 \) s with \( \dot{P}_{\text{spin}} \sim -1 \times 10^{-6} \) s s\(^{-1}\)) in the last 20 years. A Be X-ray transient, SXP 1062 (\( P_{\text{spin}} \sim 1062 \) s), also showed a fast spin-down rate of \( \dot{P}_{\text{spin}} \sim 3 \times 10^{-6} \) s s\(^{-1}\) during an outburst. These superslow pulsation neutron stars cannot be produced in the standard X-ray binary evolution model unless the neutron star has a much stronger surface magnetic field (\( B > 10^{14} \) G). The physical origin of the superslow spin period is still unclear. The possible origin and evolution channels of the superslow pulsation X-ray pulsars are discussed. Superslow pulsation X-ray pulsars could be younger X-ray binary systems, still in the fast evolution phase preceding the final equilibrium state. Alternatively, they could be a new class of neutron star system — accreting magnetars.

Keywords. stars: neutron – magnetic fields – stars : binaries : close – X-rays: binaries

1. Introduction

Recent X-ray observations discovered some superslow pulsation neutron star binaries with \( P_{\text{spin}} > 1000 \) s. In Fig. 1, the Corbet diagram for high mass X-ray binaries shows four superslow pulsation X-ray pulsars: 4U 2206+54 with \( P_{\text{spin}} \sim 5560 \) s (Wang 2009, 2010; Reig et al. 2009) and an orbital period of 19.12 days (Wang 2009); 2S 0114+65 with \( P_{\text{spin}} \sim 9600 \) s (Wang 2011) and an orbital period of 11.59 days (Crampton et al. 1985); IGR J16418-4532 with \( P_{\text{spin}} \sim 1246 \) s and \( P_{\text{orb}} \sim 3.7 \) days (Walter et al. 2006); and SXP 1062 with \( P_{\text{spin}} \sim 1062 \) s and \( P_{\text{orb}} \sim 300 \) days (Haberl et al. 2012). In addition, other possible superslow X-ray pulsar candidates were reported recently: 1E 161348-5055 in the young supernova remnant RCW 103 (\( P_{\text{spin}} \sim 6.67 \) hr, De Luca et al. 2006), and two wind-accretion symbiotic low mass X-ray binaries 4U 1954+319 (\( P_{\text{spin}} \sim 5 \) hr, Mattana et al. 2006) and IGR J16358-4724 (\( P_{\text{spin}} \sim 1.5 \) hr, Patel et al. 2004).

The spin period evolution of the new-born neutron star generally undergoes three states (Bhattacharya & van den Heuvel 1991): an ejector state in which neutron star spins down through the conventional spin-powered pulsar energy-loss mechanisms; a propeller state in which spin period decreases by means of interaction between the neutron star magnetosphere and stellar wind of the companion; and an accretor state in which the spin period of neutron star reaches a critical value, and the neutron star begins to accrete materials on to the surface, then switches on as the X-ray pulsar. The critical period is defined by equating the corotational radius of the neutron star to the magnetospheric radius, which induces the longest period of several hundred seconds but less than \( \sim 1000 \) s for the neutron star of magnetic field \( B < B_{\text{cr}} = 4.4 \times 10^{13} \) G. Then what channels
produce the superlong spin period higher than 1000 s? Thus, detailed studies of these superslow X-ray pulsars will help us to understand the evolution of neutron star binaries and physical nature of these sources.

2. Temporal and spectral properties of superslow pulsation X-ray pulsars

With the long-term INTEGRAL monitoring observations, we derived the orbital phase-resolved spectral properties for two superslow pulsation X-ray pulsars 4U 2206+54 and 2S 0114+65 (Fig. 2). The spectra are fitted with the absorbed power-law model plus high energy cut-off. The spectral variations in both two sources show a common property. There exist anti-correlations between the flux and hydrogen column density/photon index, i.e., a lower column density and harder spectrum around maximum of X-ray flux. These spectral behaviour over the orbital phase suggested that they should belong to highly obscured X-ray binary systems.

In addition, we detected two cyclotron absorption lines at $\sim 30$ keV and 60 keV in 4U 2206+54 during an active state (Wang 2009), suggesting a magnetized neutron star with the magnetic field of $\sim 3 \times 10^{12}$ G located in the binary if assuming the electron absorption case. Unfortunately, we have not found evidence for the magnetic neutron

Figure 1. The $P_{\text{spin}} - P_{\text{orb}}$ diagram for high mass X-ray binaries.

Figure 2. Spectral property variations of 4U 2206+54 (left, Wang 2012) and 2S 0114+65 (middle from RXTE data (Farrell et al. 2008) and right from IBIS data, Wang 2011) over orbital phases.
star in 2S 0114+65 with different observations (Wang 2011). While a high energy tail was discovered in the X-ray spectrum of 2S 0114+65 (Wang 2011). With detailed studies show that high column density may lead to the disappearance of the hard X-ray tails in the spectra: when the derived values of column density are higher than $\sim 3 \times 10^{22}$ cm$^{-2}$, no hard X-ray tails are detected. How to produce the hard X-ray tails above 70 keV for accreting neutron stars in high mass X-ray binaries especially in the wind-fed accretion systems is unclear. It is possible that hot corona exists near neutron stars for wind-fed accretion systems like 2S 014+65; and the dense accretion materials or strong winds prevent the formation of hot corona or depress the comptonization effects.

The long-term monitoring observations also discovered the spin evolution of these superslow pulsation X-ray pulsars. In Fig. 3, we have presented the spin evolution of 4U 2206+54 and 2S 0114+65 respectively. The pulsar in 4U 2206+54 undergone a long-term spin-down trend in the last twenty years with an average spin-down rate of $4.9 \times 10^{-7}$ s$^{-1}$ by different measurements (Wang 2010, 2012; Finger et al. 2010; Reig et al. 2012). But the spin period of the neutron star in 2S 0114+65 varies from 2.73 hr around 1986 to 2.63 hr around 2008 (Wang 2011) with the present spin-up rate of $1.09 \times 10^{-6}$ s$^{-1}$. Additionally, the spin-up rate of the neutron star in 2S 0114+65 seems to be accelerating (see Fig. 3). A slow rotation neutron star of $P_{\text{spin}} \sim 1062$ s was also discovered in a Be X-ray transient SXP 1062 (Henault-Brunet et al. 2012). During a giant outburst, a very fast spin-down rate of $\sim 3 \times 10^{-6}$ s s$^{-1}$ is discovered in this X-ray pulsar (Haberl et al. 2012).

3. Accreting Magnetars - A new class of neutron star systems?

Discovery of these superslow pulsation X-ray pulsars provides the challenge to the present evolution model of X-ray binaries. Then what is physical origin for long spin period neutron stars?

Li & van den Heuvel (1999) have suggested that neutron star spins down to the spin period range longer than 1000 s if the neutron star was born as a magnetar with an initial magnetic field $B > 10^{14}$ G. This ultra-strong magnetic field could decay to the normal value ranges of $10^{12} - 10^{13}$ G within a few million years, so that superslow pulsation X-ray pulsars may be defined as magnetar descendants.

The alternative suggestion proposed by Ikhsanov (2007) shows that an additional evo-
olution phase subsonic propeller state between the transition from known supersonic propeller state to accretor state could allow the spin period increases up to several thousand seconds without the assumption of magnetars, which is the so-called break period given by:

\[ P_{\text{br}} \simeq 2000 \frac{M_{\text{NS}}}{1.4M_\odot} \frac{-4/21}{0.3B_{\text{cr}}^{16/21}} \frac{\dot{M}}{10^{15}\text{gs}^{-1}}^{5/7} \text{s}, \]  

(3.1)

where \( B_{\text{surf}} \) is the surface magnetic field of the neutron star. However, if the above formula is applied to the case of 4U 2206+54/2S 0114+65, one find the surface magnetic field higher than \( 10^{14} \) G.

The fast spin-down rate is discovered in two superslow pulsation X-ray pulsars 4U 2206+54 and SXP 1062. According to the standard evolutionary scenario, the maximum spin-down rate in the accretor stage is \( \dot{P} \sim 2\pi B^2 R_{\text{NS}}^6 / (G M I) \), which implies \( B > 10^{14} \) G for 4U 2206+54 and SXP 1062.

Recently, a new theory of quasi-spherical accretion for X-ray pulsars is developed (Shakura et al. 2012), the magnetic field in wind-fed neutron star systems is given by

\[ B_{12} \sim 8.1 \dot{M}_{16}^{1/3} V_{300}^{-11/3} \left( \frac{P_{1000}}{P_{\text{orb}300}} \right)^{11/12} G. \]  

(3.2)

This also gives the ultrastrong magnetic field of \( > 10^{14} \) G.

Thus, these superslow pulsation pulsars could be accreting magnetars! It is still quite interesting that the discovery of the cyclotron absorption line feature around 30 keV would suggest a magnetic field of \( 3 \times 10^{12} \) G for the electron cyclotron absorption case, but a magnetic field of \( \sim 5 \times 10^{13} \) G for the proton cyclotron line assumption. Thus, difficulty and uncertainties in explaining the long spin period still exist. It is possible that superslow pulsation X-ray pulsars may not follow the present standard evolution models in close binaries.

The superslow pulsation X-ray pulsars undergo the fast spin evolution, not reaching the equilibrium. We suggested the possible evolution track among the superslow pulsation X-ray pulsars and supergiant binaries. Superslow pulsation X-ray pulsars should be younger binary systems, and after rapid spin-down and spin-up phases, they will become supergiant X-ray binaries in the equilibrium spin-period range.

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Vela Glitch Monitoring from HartRAO

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Abstract. The Vela pulsar, like many other young pulsars, undergoes occasional sudden "spin-ups" in rotational frequency known as glitches. These glitches are characterised by a sudden (less than 30s) rise in the rotation frequency accompanied by a jump in the spin-down. This is generally followed by rapidly decaying transients in the spin-down and a gradual linear recovery. This recovery provides insight into the internal structure of the neutron star.

The telescopes at HartRAO were used to monitor the Vela pulsar almost daily from 1985 in order to monitor these glitches. The vast majority of these observations were made using the 26m antenna at 1.6 GHz and 2.3 GHz. When the 26m antenna was offline due to a bearing failure for two years from 2008 the 15m MeerKAT prototype antenna was used to observe Vela.

During the entire monitoring campaign 10 large glitches have been observed. The majority of the glitches show a similar recovery pattern. We discuss the characteristics of this common recovery. We compare the standard glitch recovery to that predicted by a hydrodynamic model of the neutron star interior.

An exception to the standard glitch are the two glitches which occurred in 1994 separated by 32 days. This "double" glitch is unique amongst Vela glitches. The event is accompanied by typical transients in rotation frequency derivative but all of the long-term offset occurs at the first event and the rapidly-decaying transient is only seen with the second spin-up.
On the peculiarities in the spin-down of isolated radio pulsars

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Abstract. We investigate the spin-down behaviour of a sample of 25 radio pulsars on decadal timescales (~18 years) using a continuous timing data obtained over a period of at Hartebeesthoek Radio Astronomy Observatory (HartRAO). Particular attention is placed on achieving a better time resolution of both the short-term and long-term changes in pulsar spin-down using local phase-coherent measurements of the spin-down rates (\˙\nu). We demonstrate that the spin-down of radio pulsars is generally complicated by a superposition of processes that may or may not be related. Specifically, our results show that (i) for 7 pulsars, the observed spin-down variation is largely stochastic, characterized by random and sustained jumps in \dot{\nu} of varying amplitudes, (ii) for 9 objects, the spin-down evolution shows dominant monotonic variations in \dot{\nu} superimposed on short-term stochastic jumps in the parameter, and (iii) for the remaining 9 pulsars, the long-term spin-down evolution is non-monotonic, dominated by some systematic excursion in the measured spin-down rates.
Session 9

Pulsars and

the interstellar medium
Galactic structure and turbulence, pulsar distances, and the intergalactic medium

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Abstract. This paper summarizes how multi-wavelength measurements will be aggregated to determine Galactic structure in the interstellar medium (ISM) and produce the next-generation electron density model. Fluctuations in density and magnetic field from parsec scales down to about 1000 km cause a number of propagation effects in both radio waves and cosmic rays. Density microstructure appears to include Kolmogorov-like turbulence. The next generation electron-density model, NE2012, will include about double the number of lines of sight with dispersion and scattering measurements and it will be anchored with a much larger number of pulsar parallax distances. The foreground Galactic model is crucial for inferring similar ionized structures in the intergalactic medium (IGM) from scattering measurements on high-z objects. Intergalactic scattering is discussed with reference to distant sources of radio bursts. In particular, the cosmological radio scattering horizon is defined along with its analog for the ISM.

Keywords. plasmas, turbulence, stars: neutron, pulsars: general, ISM: magnetic fields, Galaxy: structure

1. Introduction

A detailed model for the electron density ($n_e$) of the Milky Way is needed for several fundamental reasons. A distance scale for Galactic radio pulsars is needed for establishing the space density, velocity distribution, and luminosities of neutron stars. The birth and death rates of radio pulsars and the association of pulsars with supernova remnants also rely on an accurate distance scale. Survey designs for pulsars and fast radio transients must take into account dispersion and scattering that smear pulses and reduce sensitivity. Establishing whether a fast radio transient is Galactic or extragalactic is straightforward if the range of dispersion measures (DM) from the Milky Way is known. The most extreme case is for pulsars close to Sgr A*, the black hole in the center of the Galaxy. There is strong interest in the Galactic magnetic field’s structure and how it influences cosmic-ray propagation. The best constraints on the large-scale structure of the magnetic field as well as its variations come from Faraday rotation measurements. Inverting the rotation measure (RM, the integral of electron density and parallel magnetic field) into constraints on the field requires a Galactic model for $n_e$. A Galactic model for $n_e$ and its fluctuations $\delta n_e$ allows intensity scintillations of cosmological sources (active galactic nuclei and gamma-ray burst afterglows) from the foreground interstellar medium (ISM) to be used to place constraints on source sizes. Finally, a Galactic model serves as a baseline for assessing the level of dispersion and scattering from the ionized intergalactic medium (IGM).

The NE2001 (Cordes & Lazio 2002) model has served the purposes described above since 2002. In this paper I summarize the development of a new model, NE2012, so-named because it will make use of input data that mostly obtained through the end of 2012.

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2. Quantifying the ionized ISM

A number of line-of-sight (LoS) integrated measures are used to characterize the electron density and magnetic field. DM is the integral of $n_e$ and includes variations $\delta n_e$ on any and all length scales. The scattering measure (SM) is the LoS integral of the spectral coefficient $C_n^2$ of the electron density wavenumber spectrum. Scattering measurements (including angular broadening, pulse broadening, diffractive and refractive intensity scintillations [DISS, RISS]) are interpreted, often successfully, in terms of a power-law wavenumber spectrum

$$\delta n_e^2(q) = C_n^2 q^{-\beta}, \quad \frac{2\pi}{\ell_0} \leq q \leq \frac{2\pi}{\ell_1},$$

where the outer scale $\ell_0 \sim \text{pc}$ and the inner scale $\ell_1 \sim 100\text{sc} \text{km}$. The spectral index is found to be $\beta \sim 4$ with consistency in many cases with the Kolmogorov value $\beta = 11/3$ but with other cases indicating a shallower spectrum. There is also strong evidence that fluctuations are highly anisotropic for some lines of sight, requiring a different form than in the equation, which applies to the isotropic case. Summing along an LoS will lessen the influence of anisotropies, which are likely caused by local magnetic fields that have a variety of orientations. As in NE2001 we use a cloudlet model to describe the ionized gas where microstructure in $\delta n_e$ contained inside the cloudlets is described by Kolmogorov ($\beta = 11/3$) fluctuations. These yield the relations (where $ds$ is the infinitesimal along the LoS),

$$C_n^2 \propto F n_e^2,$$
$$dDM = n_e ds,$$
$$dSM = C_n^2 ds \propto F n_e dDM,$$
$$dEM = \frac{\zeta(1 + \epsilon^2)}{\eta} n_e dDM \propto \frac{\ell_0^{2/3}(1 + \epsilon^2)}{\epsilon^2} dSM,$$
$$dRM = B_\parallel dDM,$$

where $\epsilon = \delta n_e/n_e$ is the fractional variation inside ionized clouds; $\zeta = \text{intercloud fractional variance}$; $\eta = \text{volume filling factor}$; $B_\parallel$ is the magnetic field component parallel to the LoS; and $F = \zeta^2/\eta^{2/3}$ is the “fluctuation” parameter that relates the square of the local mean electron density ($n_e$) to the spectral coefficient $C_n^2$.

3. Quick summary of electron density models

There is a long heritage of electron density models presented since the discovery of pulsars in 1967. For the most part these were simple, axisymmetric models and they did not include electron-density variations. The first model to allow predictions of scattering from $\delta n_e$ was in Cordes et al. (1991) and the first to include spiral arms and scattering was the TC93 model (Taylor & Cordes 1993), with spiral arms defined by Georgelin & Georgelin from HII regions. Another axisymmetric model without any treatment of density variations by Gómez et al. (2001; hereafter GBC01) fitted a two-disk model to only those lines of sight where an independent distance was available along with values of DM. The NE2001 model made use of a larger database of dispersion and scattering measurements than was available at the time of the TC93 model and it used a significant number (54) of parallaxes (timing and interferometric) to constrain the local ISM (LISM). The spiral arms in NE2001 had predefined central axes but their scale heights, widths, and central densities were individually fitted for. Table 1 compares the components included (as check marks) in the TC93, GBC01, and NE2001 models.
Table 1. Galactic electron density model components

<table>
<thead>
<tr>
<th>Component</th>
<th>TC93</th>
<th>GBC01</th>
<th>NE2001</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>Thick Disk</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>DM (_8) constrained</td>
</tr>
<tr>
<td>Thin Disk</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>DM vs. latitude</td>
</tr>
<tr>
<td>Spiral Arms</td>
<td>✓</td>
<td></td>
<td></td>
<td>Required by asymmetry in DM vs longitude</td>
</tr>
<tr>
<td>Local ISM</td>
<td></td>
<td></td>
<td></td>
<td>Several components in NE2001</td>
</tr>
<tr>
<td>Galactic Center</td>
<td></td>
<td></td>
<td></td>
<td>Scattering of Sgr A*, OH/IR masers; HII tracers</td>
</tr>
<tr>
<td>Clumps/Regions</td>
<td>✓</td>
<td></td>
<td></td>
<td>Identified from distance constraints or excess scattering</td>
</tr>
<tr>
<td>Voids</td>
<td>✓</td>
<td></td>
<td></td>
<td>Phase structure of ISM, chimneys; identified as with clumps/voids</td>
</tr>
<tr>
<td>Galactic Bar</td>
<td>✓</td>
<td></td>
<td></td>
<td>Stellar dynamics; no signal in DM or SM</td>
</tr>
</tbody>
</table>

One of the simplest tests of any electron density model is to check whether the DM of a known pulsar can be accounted for. Figure 1 shows Aitoff projections in Galactic coordinates of deficits in DM for the three models. Deficits were calculated as the difference of each pulsar’s DM and the integral of the model to a distance of 100 kpc. Out of 1943 pulsars with DM values, about 15% have deficits using the GBC01 model, compared to 13% for the TC93 model and less than 2% for NE2001. In all three cases, 19 pulsars in the Magellanic clouds contribute to the number of deficits; since none of the models include LMC and SMC components, the number of deficits should be reduced by this number. For NE2001 this implies that less than 1% of the catalogued pulsars show deficits. The most prominent deficits in the GBC01 and TC93 models are in the Galactic plane and correspond to directions where spiral arms contribute to the electron density. The large number of deficits for the symmetric GBC01 model is not surprising. The spiral arms of the TC93 model clearly cannot provide enough electrons and, in fact, the NE2001 model explicitly addressed this problem using the data available in 2001 (e.g. 1143 DM values). Clearly, NE2001 stands up well against the 800 additional pulsars now available.

4. How does NE2001 measure up?

The DM-deficit test shows only necessity and not sufficiency for any model. For example, a model could provide too many electrons and pass the DM-deficit test while providing highly biased distance estimates. It appears that in some directions, NE2001 does mis-estimate distances, although as both under-and-over predictions (e.g. Chatterjee et al. 2009). Figure 1 also shows a comparison of parallax and NE2001/DM distances for 54 pulsars. 70% of the objects have consistent parallax and DM distances to within 20%, while 17% have more than a factor of two discrepancy (7 objects nearer and 2 objects further than the DM distance) and 13% are discrepant by a factor of 0.2 to 2; for these 13%, the true distance is larger than the DM distance. These results indicate, unsurprisingly, that there is unmodeled Galactic structure in the form of both voids and enhancements in electron density. A simple change in scale height of the thick disk is not sufficient to rectify these differences.

Other diagnostics of the electron density model include a comparison of the implied emission measure (EM) in the direction of high-latitude pulsars and the scale height of pulsars for in different directions. Emission measures from the WHAM H\(\alpha\) survey compared with EM calculated from NE2001 using the cloudlet formalism suggest that the overall filling factor for electron density increases with distance \(|z|\) from the Galactic plane and that there may be a larger scale height and lower mid-plane density for the thick disk (Berkhuijsen et al. 2006, Gaensler et al. 2008). Comparisons of SM and EM are challenging because the corresponding integrals are over different distances. That particular issue is alleviated for globular cluster pulsars at high latitudes that are well above the electron-density scale height. However, calculations of EM from SM must use
an appropriate value of the outer scale (cf. Eq. 2.2), introducing another variable into the problem. Also, previous analyses have not included the extra variance in electron density due to the Kolmogorov turbulence internal to clouds (as quantified by the parameter $\epsilon$ above). The pulsar scale height deduced from pulsar surveys after correction for selection effects suggests that distances are underestimated by NE2001 because distant pulsars in the inner Galaxy have a smaller nominal height than do those near the Sun (Kramer et al. 2003; Lorimer et al. 2006). However the scale height should be somewhat smaller toward the inner Galaxy in accordance with the larger gravitational potential.

5. Development of NE2012

NE2012 is the next generation electron-density model. It will include all of the same components as NE2001 but all assumptions and methodologies are being revisited. The new model will make use of the much larger database of DM and SM values that have emerged over the last 10+ years from pulsar surveys along with scattering measurements of extragalactic sources. In addition, the number of pulsar parallaxes will have increased by a factor $> 5$, allowing major components of the new model to be nailed down. A new element of the model construction will involve usage of Faraday rotation measures of pulsars and extragalactic sources, which also introduces additional model parameters, but allows both the electron density and the Galactic magnetic field to be better modeled. H$\alpha$ measurements (EM) and Galactic synchrotron radiation define spiral arms and

Figure 1. Plots of DM deficits for three electron density models. Models were tested with 1943 pulsars that have values of DM in the ATNF pulsar catalog (Manchester et al. 2005; http://www.atnf.csiro.au/research/pulsar/psrcat). Plotted circles show pulsars whose DMs are larger than can be accounted for by the model. In order of circle size, the model deficits are $\Delta$DM $< 10$ pc cm$^{-3}$, 10 to 50 pc cm$^{-3}$, 50 to 100 pc cm$^{-3}$, and $> 50$ pc cm$^{-3}$. Top left panel: deficits for the GBC01 model (301 pulsars); Top right panel: deficits for TC93 (248 pulsars); Bottom left panel: deficits for NE2001 (34 pulsars); Bottom right panel: Comparison of parallax distances and DM distances from the NE2001 model for 54 pulsars. Squares show DM and parallax distances that are consistent to within 20%. Circles indicate pulsars with differences of 20-50% (small circles) and $> 50%$ (large circles). A plus (minus) sign implies that the parallax distance is larger (smaller) than the DM distance.
the large scale magnetic field. Additional new input will include constraints on Galactic
structure from the Spitzer/GLIMPSE survey (Churchwell et al. 2009), from the kine-
matics of methanol masers (Sanna et al. 2009), and from distance constraints on discrete
ionized regions using the scintillation arc phenomenon (Stinebring et al. 2001). Also, the
distance to the Galactic center is now being tightened up at a value not dissimilar to the
official IAU distance of 8.5 kpc.

A major uncertainty that remains is the spiral-arm structure of the Galaxy. While the
GLIMPSE survey categorically states that the Milky Way is a grand-design, two-armed
spiral galaxy (Churchwell et al. 2009), studies of methanol masers favor a four-armed
spiral as does a study of Faraday rotation measures and HII regions (Hou et al. 2009).
The approach that will be taken in developing NE2012 is to consider several alternative
structures as guided by these ancillary studies. Segments of some spiral arms may also
be definable using DM and SM data combined with parallax measurements alone.

Development of the next generation model will proceed in stages. The first will not
include Faraday rotation data and the complexities of the Galactic magnetic field. Suc-
ceeding stages will include the magnetic field and new pulsar parallaxes that will emerge
over the next year. Accordingly, NE2012 will be rolled out in a series of versions.

6. Scattering of extragalactic sources

Two areas are of particular interest: (1) Using scattering measurements to probe the
properties of the IGM; and (2) Assessing the reality and distances of fast transient sources
that appear to be extragalactic.

Relevant sources include AGNs for which angular broadening has been measured or, in
the case of intra-day variable (IDV) sources, that show RISS from foreground Galactic gas
(e.g. Bignall et al. 2009). The measured angular broadening of some of these sources (i.e.
after untangling scattering broadening from the intrinsic source size) potentially includes
scattering in the IGM that adds to scattering from turbulence in the host galaxy of the
source, in intervening galaxies, and in the Milky Way. While a complete analysis is not
yet done, it is clear that scattering in the IGM is smaller than the angular broadening
caused by the Milky Way. There are hints, however, that IGM scattering can be discerned
as a slight excess over the Galactic contribution. To establish IGM scattering, Galactic
scattering needs to be assessed carefully using a large number of measurements of AGNs
to calibrate the Galactic electron density model. IDV sources indicate that apparent
source sizes are as small as $\sim 10 \mu$arc sec as seen by an observer just outside the Milky
Way (in order that RISS on intra-day time scales can occur), suggesting that at least for
some lines of sight, IGM scattering is no larger than these angular sizes.

Fast transients — those short enough that dispersion and scattering are important —
are of great interest and a few candidate events have been seen with large-enough DM
to conclude that they may be extragalactic in origin.

Pulse broadening causes the detectability of fast transients to degrade over and above
the effects of the inverse square law. Pulses will be selected against if scattering broaden-
ing is larger than the intrinsic pulse width $W$. We define the Galactic horizon in terms of
DM by requiring that $\tau_d \lesssim W$. Figure 2 shows the expected distribution of $\tau_d$ for Galactic
sources along with the IGM contribution to DM vs redshift. For 1 ms pulses, the horizon
is about 5 kpc at 1 GHz while 1 $\mu$s pulses can be seen to only 2.4 kpc at 1 GHz. These
values apply only to sources within the Galactic disk. Looking perpendicular to the disk,
the seeing distance “breaks out” if it is more than about 1 kpc. At low frequencies, e.g.
100 MHz, a 1 $\mu$s pulse can be seen only to about 100 pc.

The cosmological horizon can be calculated form the variation of DM with redshift $z$
Figure 2. Left: Histogram of the pulse broadening time expected from sources distributed throughout the disk of the Milky Way, defined as a disk of radius 10 kpc and thickness 1 kpc. The scattering measure and pulse broadening were calculated using the NE2001 model (Cordes & Lazio 2002). The bottom horizontal scale gives values for a radio frequency of 1 GHz and the top axis for 100 MHz. Right: Dispersion measure from the intergalactic medium for a ΛCDM cosmology with Ω_M0 = -0.27, Ω_b0 = 0.046, and H_0 = 70.4 km s^-1 Mpc^-1.

assuming that the IGM is completely ionized and that the relationship of pulse broadening time to DM is the same as for Galactic sources; this is at best a very crude approach. We find that a 1 ms pulse can be detected to z ≈ 0.2 and the broadening is τ_d ~ 100 ms for transients originating at z = 1.

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Interstellar scattering — New diagnostics of pulsars and the ISM

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Abstract. Extreme Scattering Events and pulsar secondary spectra have highlighted fundamental problems in our understanding of the dynamics of interstellar turbulence. We describe some of these problems in detail and present the theory behind the technique of speckle imaging, which offers a prospect of revealing fundamental properties of the turbulence. It also offers the prospect of resolving pulsar magnetospheres on \( \sim 10 \text{nas} \) scales.

Keywords. scattering, turbulence, ISM: structure, ISM: magnetic fields

1. Why bother about turbulence?

Compilations of pulsar scattering observations reveal that, in some average sense, the power spectrum of electron density fluctuations in the ISM follows a power law on scales from \( \sim 10^6 \text{m} \) up to \( 10^{14\sim 18} \text{m} \), with a power-law index close to \( 11/3 \), the value expected from Kolmogorov turbulence (Armstrong, Rickett & Spangler 1995). In the Kolmogorov view of turbulence, mechanical and magnetic energy from macroscopic processes, such as stellar winds and explosions, cascades to smaller scales via a succession of self-similar kinetic-energy conserving turbulent eddies. It is surprising that the predictions of Kolmogorov theory, which applies to incompressible hydrodynamic turbulence, should resemble in any way the structure of the interstellar medium.

The ISM is not incompressible over a large range of scales of interest (Luo & Melrose 2006), and is intrinsically magneto-hydrodynamic. Indeed, the magnetic field must play a strong role in mediating the interstellar turbulent cascade because the presence of diffractive scintillation in pulsars shows that turbulence persists on scales many orders of magnitude below the collisional mean free paths of electrons and protons (Lithwick & Goldreich 2001). Moreover, there is no consensus on the most basic physics of how energy is mediated between large and small scales in the highly magnetized ISM, nor is there agreement on the interrelation between the turbulent velocity, magnetic field and density fluctuations (Elmegreen & Scalo 2004, §4.12-13).

Several key observations over the last decade have added a number of complications to our view of interstellar turbulence. The most notable has been the realization that there exist local pockets of anomalously strong turbulence. This is evident in the intermittency of scintillations of intra-day variable quasars (Lovell et al. 2008). It is also manifest in the anomalous turbulence associated with tiny (\( \sim 10^{11} \text{m} \)) ionized clouds that are prevalent throughout the ISM and that are responsible for Extreme Scattering Events (Fielder et al. 1987). The discovery of strong parabolic arcs in the secondary spectra of many pulsars has also revealed that in many instances the scattering is often highly localized along the line of sight, and that the turbulence itself appears to be highly anisotropic. Attempts
to incorporate these anomalous properties into a physical framework of the ISM have proven problematic and controversial (Spangler & Vazquez-Semadeni 2007).

We elucidate the problems exposed by ESEs and pulsar secondary spectra in §2, while §3 describes the method of speckle imaging that is allowing us to directly “image” these scattering structures in the ISM. In §4 we present some preliminary limits on the nanosecond structure of the pulsars whose radiation is being scattered by some of these anomalous scattering structures. The final section describes the prospects for solving some of the fundamental questions that relate to interstellar turbulence.

2. ESEs, Parabolic Arcs and Anisotropic scattering

Extreme Scattering Events (ESEs) are intensity excursions exhibited by some compact quasars and pulsars and lasting between 10 and 50 days (Fiedler et al. 1987; Romani et al. 1987). The symmetric nature of their lightcurves argues that they are due to the passage of 4-70×10^{10} m sized cloud-like features across the lines of sight. The observed event rate of 0.013 source^{-1} year^{-1} means that the clouds are common, with an estimated volume density of one per ∼10^{-5} pc^{4} (Fiedler et al. 1994; Walker & Wardle 1998).

The existence of ESEs is problematic because their observed optical properties imply, at face value, internal pressures that exceed the diffuse ISM’s by three orders of magnitude, assuming temperatures comparable to the diffuse warm ISM (Spangler & Vazquez-Semadeni 2007). In a simple model in which a plasma overdensity refracts the radio waves sufficiently to reproduce the caustic peaks observed in ESE lightcurves, column densities of ∼10^{19} cm^{-2} are required. The volume density depends on the elongation of the structure along the line of sight; for an elongation η = 100D_{p} the density is ∼10^{5} η^{-2} cm^{-3} (Romani et al. 1987). However, other models may explain ESEs without recourse to such extreme properties; Pen & King (2012) have recently proposed that ESE may instead be interpreted in terms of underdense sheets in the ISM.

There is evidence from pulsar scattering that much of the turbulence in the ISM is highly localised and anisotropic. One of the principal means of gleaning this information from pulsar scattering measurements is via the secondary spectrum. The secondary spectrum, A(τ,ω), is the squared amplitude of the two dimensional Fourier transform of the dynamic spectrum of a pulsar’s intensity scintillations, I(ν,t). In the secondary spectrum, the conjugate of observing frequency is the delay, while the Fourier conjugate of time is Doppler frequency. In the regime of strong scattering from a thin scattering screen, one can represent the received wavefield as the sum of wavefields from a set of stationary phase points (or speckles) on the surface of the scattering disk, u = \sum a_{j}e^{i\Phi_{j}}, with each stationary phase point possessing an amplitude a_{j} and phase \Phi_{j} = \delta (x_{j} - \beta r)^{2}/2\nu^{2}, where \delta (x_{j}) is the phase delay imposed by the scattering medium at the position, x_{j}, of the stationary phase point, and r is the location of the telescope on the observer’s plane. The distance to the scattering screen, D_{s}, and the distance to the pulsar, D_{p}, also effect the total phase delay via the Fresnel scale, r_{F} = (\beta D_{s}/k)^{1/2}, where β = 1 - D_{s}/D_{p}. The speckles emanate from positions \theta_{j} = (x_{j} - \beta r)/D_{s} on the scattering disk.

The intensity scintillation pattern, I(ν,t) = uu^{*}, is the result of the interference of every speckle on the scattering disk, and the resulting secondary spectrum takes the form (e.g. Walker et al. 2004),

\[ A(\tau,\omega) \propto \sum_{j,k} a_{j}a_{k} [\delta(\tau - \tau_{jk})\delta(\omega - \omega_{jk}) + \delta(\tau + \tau_{jk})\delta(\omega + \omega_{jk})], \tag{2.1} \]

where \tau_{jk} = \frac{D_{s}}{2c\beta}(\theta_{j}^{2} - \theta_{k}^{2}) + \left[ \frac{\phi_{j}}{2\pi\nu} - \frac{\phi_{k}}{2\pi\nu} \right], \quad \omega_{jk} = \frac{1}{\lambda} (\theta_{j} - \theta_{k}) \cdot v_{eff}. \tag{2.2}
The location of power in the secondary spectrum is predominately dictated by the positions of the speckles. For any given pair of speckles, $j$ and $k$, power appears at both the co-ordinates $(\tau_{jk}, \omega_{jk})$ and $(-\tau_{jk}, -\omega_{jk})$. This symmetry is a reflection of the fact that $A(\tau, \omega)$ is derived from the Fourier transform of a real quantity, namely $I(\nu, t)$. The effective scintillation velocity, $v_{\text{eff}}$ also influences the Doppler frequency of the speckles; it is usually dominated by the pulsar velocity, $v_p$, but it may in principle also be affected by the peculiar velocity of the screen, $v_s$, or of the Earth, $v_\oplus$: $v_{\text{eff}} = \beta^{-1} v_{\text{ISS}} = \beta^{-1} [(1 - \beta) v_p + \beta v_\oplus - v_s]$.

The prescription given by eqs. (2.1)-(2.2) affords a geometric interpretation of the secondary spectrum. Consider interference caused by a highly elongated speckle pattern, in which all the speckles make a constant angle, $\alpha$, to the scintillation velocity. Interference between a speckle at location $\theta_j$ with the bright “core” of the image at $\theta_k = 0$ traces out a parabola with the locus $(\tau_0, \omega_0) = (D_s \theta_0^2 / 2c \beta, \theta_j v_{\text{eff}} \cos \alpha / \lambda)$. Allowing variation in $\theta_k \neq 0$, we obtain the locus of an inverted parabolae whose apex occurs at co-ordinates $(\tau_0, \omega_0)$. If, instead, the distribution of speckles is not highly elongated, variations in $\alpha$ cause power to lie interior to a bounding parabola, as shown in Figure 1.

Many pulsars exhibit strong, sharply defined parabolic arcs of the sort seen in the right of Figure 1. This reveals two important qualities of the scattering. 1. The scattering is highly anisotropic. If it were otherwise, power in the secondary spectrum would instead lie interior to the main parabola. 2. The scattering occurs in localized patches, on a scattering screen that is thin, a few percent of the total pulsar distance. Variation in $D_s$ and $\beta$ would otherwise smear out the locations of points in the secondary spectrum.

Unfortunately, eqs. (2.1)-(2.2) do not enable an unambiguous reconstruction of the speckle distribution because the angle $\alpha$ is not known for any given speckle. The delay only measures $\theta_j^2$ and the Doppler frequency only measures $\theta_j v_{\text{eff}} \cos \alpha / \lambda$. This degeneracy can be broken by instead measuring the scintillations in the interferometric visibility on intercontinental baselines, as we now describe.

### 3. Speckle Imaging

It is possible to form a complete image of the distribution of speckles on the scattering disk by forming the secondary spectrum of the interferometric visibility. As we show below, the distribution of power in the visibility secondary spectrum is very close to that observed in the intensity secondary spectrum, but the visibilities provide information on

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† The terms in square brackets in eq. (2.2) make only a small contribution to the overall delay.
the astrometric phase shift associated with each pair of speckles. In essence, one is able to image the disk by using the secondary spectrum to isolate the wavefield of each pair of interfering speckles, and then measure the phase of this isolated wavefield from the visibility secondary spectrum to localise the speckle positions to extremely high precision.

To see how this works, consider the visibility that a two-element interferometer would measure from a scattered pulsar. Quantities measured with the first and second receiving elements are labelled with subscripts 1 and 2 respectively. The elements are placed at locations \( \mathbf{r}_1 = \mathbf{R} - \Delta \mathbf{r}/2 \) and \( \mathbf{r}_2 = \mathbf{R} + \Delta \mathbf{r}/2 \) on the observer’s plane, with \( \mathbf{R} \) the mean position of the telescopes, and \( \Delta \mathbf{r} \) their relative displacement. The measured visibility is,

\[
V(\nu, t) = u_1 u_2^* = \sum_{j,k} a_{1,j} a_{2,k} \cos(\Phi_{1,j} - \Phi_{2,k}) + i \sin(\Phi_{1,j} - \Phi_{2,k}),
\]

(3.1)

where \( \Phi_{jk} = \Phi_{1,j} - \Phi_{2,k} \) is the phase difference between the \( j \)th stationary phase point measured at station 1 and the \( k \)th stationary phase point measured at station 2. In the limit in which the bandwidth and observing duration are large, the Fourier-transform of the visibility dynamic spectrum reduces to,

\[
\tilde{V}(\tau, \omega) = \frac{1}{2\pi} \sum_{j,k} a_{1,j} a_{2,k} \left\{ \exp[i \Phi^0_{jk}] \delta(\tau + \tau_{jk}) \delta(\omega + \omega_{jk}) \right\},
\]

(3.2)

\[
\omega_{jk} = \frac{1}{2\pi} \frac{\partial (\Phi_{1,j} - \Phi_{2,k})}{\partial \nu} = \frac{1}{\lambda \beta} (\theta_{1,j} - \theta_{2,k}) \cdot \mathbf{v}_{\text{eff}} + \frac{\beta}{\lambda D_s} \Delta \mathbf{r} \cdot \mathbf{v}_{\text{eff}},
\]

(3.3)

\[
\tau_{jk} = \frac{1}{2\pi} \frac{\partial (\Phi_{1,j} - \Phi_{2,k})}{\partial \nu} = \frac{D_s (\theta_{1,j}^2 - \theta_{2,k}^2)}{2c \beta} + (\theta_{1,j} + \theta_{2,k}) \cdot \mathbf{v}_{\text{eff}}.
\]

(3.4)

\[
\Phi^0_{jk} = \phi_j - \phi_k + \frac{D_s^2}{2c \nu} (\theta_{1,j}^2 - \theta_{2,k}^2) - \frac{\beta D_s}{2\pi \nu} (\theta_{1,j} + \theta_{2,k}) \cdot \Delta \mathbf{r},
\]

(3.5)

where we write \( \theta_{1,j} = (\mathbf{x}_j - \beta \mathbf{R})/D_s, \quad \theta_{2,k} = (\mathbf{x}_k - \beta \mathbf{R})/D_s \). Unlike its single-dish counterpart, the visibility secondary spectrum is not symmetric under the operation \( (\tau, \omega) \rightarrow (-\tau, -\omega) \). This is because \( \omega_{jk} \neq -\omega_{kj} \) and \( \tau_{jk} \neq -\tau_{kj} \). However, if the visibilities are measured on a baseline small compared to the scale of the scintillation pattern (i.e. \( \Delta \mathbf{r} \ll D_s \theta_j \)), the amplitude of the visibility secondary spectrum is effectively identical to that observed in the intensity secondary spectrum.

An important difference between the intensity and visibility secondary spectrum is that the latter contains an \( \exp[i \Phi^0_{jk}] \) phase term that is no longer antisymmetric. This is because the phase of each speckle measured at two widely-separated telescopes differs slightly because of astrometric phase term. In terms of the formalism introduced here, we see that when \( \Delta \mathbf{r} = 0 \), the term proportional to the \( \theta_j + \theta_k \cdot \Delta \mathbf{r} \) destroys the odd symmetry \( \Phi^0_{jk} = -\Phi^0_{kj} \). If one adds the contribution from the \( j, k \) and \( k, j \) terms in the secondary spectrum, it is possible to isolate the astrometric phase of each pair of speckles and determine the projection of the position of each pair of speckles, \( \theta_j + \theta_k \) along the baseline \( \Delta \mathbf{r} \). Thus, measurements along two baselines are sufficient to determine the position of each pair of speckles. This is the basis of scintillation speckle imaging.

This technique was first applied to PSR B0834+06 by Brisken et al. (2010). These 327 MHz observations revealed a number of intriguing properties of the scattering medium:

- The scattering disk was composed of two separate structures, separated by 9 AU.
- Speckles along the primary scattering disk, which was 16 AU long, were distributed anisotropically, with the ratio of the major to minor axis of the disk being at least 27:1.
The distribution of speckles along the long axis of the primary scattering disk does not resemble that expected of Kolmogorov turbulence.

- The secondary scattering disk contributed about 4% of the total power. It is tempting to speculate on the origin of this feature. One possibility, given the strong scattering properties the feature must possess in order to scatter a substantial amount of off-axis power back into the line of sight, is that it may be a cloud of the sort that is implicated in Extreme Scattering Events. This hypothesis, however, is difficult to test because ESEs are characterised by their optical properties when viewed on-axis with respect to a background source, whereas this object was off-axis by > 20 mas.

3.1. Magnetic field limits

Given the highly anisotropic scattering inferred towards PSR B0834+06 and other pulsars which display strong parabolic arcs, it seems clear that the magnetic field plays an important role in the turbulent dynamics. One means of probing the magnetic field is to search for small rotation measure (RM) fluctuations associated with the scattering medium. If RM fluctuations are present, the left and right-hand circularly polarized components of the pulsar radiation will experience slightly different phase delays, and this will cause different scintillations in each sense of circular polarization (Macquart & Melrose 2000), which would be visible in the circular polarization secondary spectrum.

Brisken et al. (2010) report that, for PSR B0834+06, no detectable scintillating circular polarization signal was detected at the 0.1% level, and this places a limit on the RM difference of less than $1.2 \times 10^{-3}$ rad m$^{-2}$ across AU scales on the scattering disk.

4. ISS as probes of nano-arcsecond pulsar structure

The fact that speckle images exhibit structure across baselines of > 10 AU implies stringent constraints on the size of the pulsar emission region. Interference between the primary and secondary scattering disks in the case of PSR B0834+06 means that the radiation from the pulsar is at least partially coherent on a baseline of $\delta = 1.3 \times 10^{11}$ m as viewed at the scattering screen. This translates to a physical scale at the pulsar of $\delta (D_s - D_p) = 4700$ km. If the pulsar radiation had a gaussian angular brightness profile, the HWHM of the brightness distribution would be $\sim 850$ km.

Although the radiation must be at least partially coherent on 9 AU baselines, it is difficult to determine the degree of coherence. This is because one does not know what fraction of the total power should be received from the secondary scattering disk if the pulsar radiation were 100% spatially coherent on this baseline. One can in principle determine this by comparing the power associated with the interference between pairs of speckles on the primary disk, $P_{1-1}$, and pairs of speckles on the secondary scattering disk, $P_{2-2}$, with the power associated with interference between speckles on the primary disk with those on the secondary disk, $P_{1-2}$. The pulsar is resolved if the quantity, $R = P_{1-1}P_{2-2}/P_{1-2}^2$, significantly exceeds one. Figure 2 shows that $P_{1-1}$, $P_{2-2}$ and $P_{1-2}$ can all be measured from the secondary spectrum. However, a complication arises because these three power quantities can be difficult to measure in practice, and it is difficult to relate $R$ to a specific measurement of the pulsar angular size.

5. The Future

There are two obvious prospects for progress in this field at present. The first, involving interstellar holography, which is not discussed in this short paper, has been advanced by the efforts of Walker et al. (2005, 2008). Holography takes advantage of the highly
Figure 2. A schematic of the secondary spectrum of PSR 0834+06 found by Brisken et al. (2010). The green points represent interference between speckles on the primary scattering disk, cyan represents interference between speckle pairs on the primary disk with those on the secondary scattering disk, and the purple points represent interference between adjacent speckles on the secondary scattering disk.

redundant information provided in the dynamic spectrum about the speckle distribution: for N speckles there are $N(N-1)/2$ interfering pairs measured in the secondary spectrum. The concept of interstellar holography may be viewed as a deconvolution problem. The Fourier transform of the intensity $I(\nu, t) = u(\nu, t)u^*(\nu, t)$, is just the autoconvolution of the Fourier-transformed wavefield: $\tilde{I}(\tau, \omega) = \tilde{u}(\tau, \omega) \ast \tilde{u}^*(\tau, \omega)$.

Recent holographic work performed by Ue-Li Pen and collaborators on PSR B0834+06 data has claimed a measurement of the pulsar’s reflex motion (Pen et al. in prep.). Holography was used to effectively descatter the pulsar radiation and permit extremely high S/N measurements of the pulsar’s radiation. By performing this holography over a succession of bins in pulse phase, it has been possible to measure a small but significant phase shift associated with the pulsar reflex motion.

A second prospect is related to measuring the motions of speckles in scattered pulsar images using a succession of speckle images over a period of weeks to months. In most cases, the pulsar proper motion dominates the effective scintillation velocity, but ultra-high S/N astrometric imaging, of the sort performed on PSR B0834+06, offers the prospect of resolving motions of the individual speckle groups relative to the bulk motion. This therefore offers the prospect of relating the density fluctuations associated with the scattering disk (which are, to some limited extent, recoverable with holographic techniques) with the underlying turbulent velocity fluctuations.

References
Pulsars as excellent probes for the magnetic structure in our Milky Way

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Abstract. In this invited talk, I first discuss the advantages and disadvantages of many probes for the magnetic fields of the Milky Way. I conclude that pulsars are the best probes for the magnetic structure in our Galaxy, because magnetic field strength and directions can be derived from their dispersion measures (DMs) and rotation measures (RMs). Using the pulsars as probes, magnetic field structures in the Galactic disk, especially the field reversals between the arms and interarm regions, can be well revealed from the distribution of RM data. The field strengths on large scales and small scales can be derived from RM and DM data. RMs of extragalactic radio sources can be used as the indication of magnetic field directions in the spiral tangential regions, and can be used as probes for the magnetic fields in the regions farther away than pulsars when their median RMs are compared with pulsar RMs.

Keywords. pulsars: general, ISM: magnetic fields, Galaxy: structure

1. Introduction

Magnetic fields permeate the interstellar medium on all scales, from the stellar scale of AU size to the galactic scale of tens of kpc. In general, magnetic fields are tangled by many physical processes in the interstellar medium, for example, the localized processes of star formation and supernova explosion, the galactic processes of differential rotation, density wave and stream motion, so that the ever-existed large-scale magnetic fields are very distorted. When we try to understand the properties of magnetic fields in our Milky Way, we have to know the magnetic fields of different scales in different regions.

There are many probes for the magnetic fields in our Milky Way. The most widely used are the starlight polarization, the polarized emission of dust and clouds at millimeter and submillimeter wavelength, the Zeeman effect of spectral lines or maser line from clouds or clumps, the diffuse radio synchrotron emission from relativistic electrons in the interstellar magnetic fields, the Faraday rotation of extragalactic radio sources and pulsars. The first three are related to magnetic field in clouds, and the later two are related to the fields in the diffuse medium. Each probe measures only one of the three dimensional field components or their average or integration. We have to understand the advantages and disadvantages of these probes, and then “connect” all measurements to get the real structure of the Galactic magnetic fields.

2. Advantage and disadvantage of different probes for magnetic fields

Some of the above mentioned probes are more suitable to reveal the localized magnetic fields, and some are more sensitive to the large-scale fields. Because of our location at the disk edge in the Milky Way, the best probes for the Galactic magnetic structure have to be able to detect the magnetic component parallel to the line of sight.
2.1. Starlight polarization

Starlight is not polarized when it is radiated. It becomes polarized when it passes through the interstellar medium. It is slightly absorbed or scattered by interstellar dust grains which are preferentially aligned by interstellar magnetic fields. The farther the star is, the more extinction its light suffers on the path to us, and the higher the polarization of starlight. Starlight polarization is the measurement of the summed extinction due to dusts in the path, therefore it indicates the averaged magnetic field orientations in the sky plane, not directions.

The polarization of stars around an individual cloud can be used to trace the magnetic field orientation inside the cloud. When more and more stars are observed in the very deep Galactic disk, the data can not separate magnetic field orientations in every clouds at different distances which on average are generally aligned with the Galactic plane. Therefore, the starlight probes can not be used for the large-scale magnetic structure in the Galactic disk. They are good probes for the local halo fields if a large number of high-latitude distant stars are observed in wide sky area.

2.2. Polarized emission of dust and clouds

The polarized emission from the clouds or dust is quite localized feature, and can show the magnetic field orientations in the clouds perpendicular to the line of sight. There is evidence that the magnetic fields in clouds are related to the fields of larger scales (Li & Henning 2011). Similar to the starlight probes, even if the magnetic orientations of many clouds in the disk of the Milky way are observed, we cannot get the large-scale magnetic structure, because the field orientation of all clouds are aligned with the Galactic plane in general. In fact, the polarized emission of dust and clouds has already been seen clearly from the polarization maps of WMAP or Planck, which indicate such parallel fields to the Galactic plane.

2.3. The Zeeman effect of spectral lines from clouds or clumps

The line emission or absorption from the clouds or clumps with internal magnetic fields show Zeeman splitting of the line. The separation of the split lines measures the field strength of the magnetic component parallel to the line of sight, and the sense change of circular polarization of the split lines indicates the direction of the field component on the line of sight. Physically the measurements are sensitive only to the fields inside the clouds or clumps, which are of a scale of pc or even AU. Surprisingly, the distribution of available magnetic field measurements from maser lines around HII regions are very coherent with the large-scale spiral structure and large-scale magnetic fields (Han & Zhang 2007). A big project using the ATCA (Green et al. 2012) is in progress for extensive observations of the Zeeman splitting of lines from HII regions for large-scale magnetic structure.

2.4. Diffuse radio synchrotron emission and polarization

The polarization of synchrotron radiation from relativistic electrons shows the average orientation of magnetic fields in the sky plane in the emission region, perpendicular to the line of sight. If random magnetic fields dominate in the emission region, as is often the case, then polarization “vectors” (orientation, not direction) could be very random, and the observed emission is depolarized. The polarized emission from different regions inside the Milky Way at different distances also suffers different Faraday rotations when it propagates in the interstellar medium. As we are located on the edge of the disk of the Milky Way, the observed synchrotron radiation is the superposition of such variously Faraday-rotated polarized radiation from everywhere at all distances until the Milky way...
“boundary”, which could be therefore very depolarized. The lower the observational frequency, the stronger the depolarization. The closer towards the Galactic Center along the Galactic plane, the less ordered the polarization. In the outer region near the antecenter of the Milky way, the radio emission comes from only the Perseus arm, and we see more polarized emission than in the inner Galaxy (Xiao et al. 2011).

Using the polarization survey of radio synchrotron of the whole sky, one can get some constraints on the magnetic fields in the halo of Milky Way, but it is hard to constrain the magnetic fields in the Galactic disk. Because there is no linearity for Faraday rotation against distance, and because the similarly polarized emission can come from regions of different distances, the rotation measure synthesis cannot separate the polarized emission from different regions.

### 2.5. Rotation measures of extragalactic radio sources

Faraday rotation is the summed rotation of the polarization angle $\phi$ of a linearly polarized wave on the way from a source ($\phi_0$) to us, $\phi = RM \cdot \lambda^2 + \phi_0$. The rotation measure (RM) is related to electron density and magnetic fields by $RM = 0.810 \int \text{source} n_e \mathbf{B} \cdot d\mathbf{l}$ (in unit of rad m$^{-2}$). Here $n_e$ is the electron density in cm$^{-3}$, $\mathbf{B}$ is the vector magnetic field in $\mu$G and $d\mathbf{l}$ is an elemental vector along the line of sight toward us in pc. Obviously, the RM is sensitive to the magnetic field component on the line of sight, weighted by the electron density. Notice that it is an integrated value. Positive RMs correspond to the average fields on the path directed toward us. Random or smaller-scale fields on the path cannot be recognized from the final observed wavelength dependence of $\phi$.

There are many background extragalactic radio sources (EGRs) distributed in the sky, which can be the most powerful probe of the magnetic field in the halo of our Milky Way. The observed RMs contain three contributions: 1) the intrinsic RM from the source, which depends on the observational wavelength and how deep in the source the radiation comes from, 2) the RM of intergalactic medium which is probably very small and not measured yet, and 3) the RM foreground from our Milky Way. The RMs of a number of EGRs in a given sky region should have more or less the common foreground Galactic RM contribution. The large-scale RM sky distribution therefore shows the magnetic fields in the halo (Han et al. 1997, 1999). The RM sky of more dense data set (Taylor et al. 2009, Oppermann et al. 2012) can show the details of magnetic fields in visually large objects (Harvey-Smith et al. 2011), in addition to the general RM sky of large angular scales.

At lower Galactic latitudes, extensive efforts have recently been made to enlarge the RM samples (e.g. Brown et al. 2007, Van Eck et al. 2011). Towards the central region the data become more scarce, because the diffuse emission is stronger and because the polarization observations are more difficult to carry out. The median RMs of background EGRs behind the disk are the integrated measurement of polarization angle rotations over the whole path in the disk and therefore not sensitive to the possible magnetic field reversals between arms and interarm regions on the path. The dominant contribution to RMs of EGRs comes from tangential regions, where the magnetic fields have the smallest angle with the line of sight if the fields follow spiral arms. When a set of RMs of EGRs are fitted with a magnetic structure model, the electron density model is a necessary independent input.

### 3. Pulsars as probes for the Galactic magnetic fields

Pulsars are polarized radio sources inside our Milky Way. The observed RMs of pulsars come only from the interstellar medium between pulsars and us, because there is no
Figure 1. The RM distribution of 736 pulsars of $|b| < 8^\circ$ projected onto the Galactic plane, including new data of Han et al. (2012, in preparation). The linear sizes of the symbols are proportional to the square root of the RM values with limits of $\pm 27$ and $\pm 2700$ rad m$^{-2}$. Positive RMs are shown by plus signs and negative RMs by open circles. The background shows the approximate locations of spiral arms used in the NE2001 electron density model. Published RMs of EGRs of $|b| < 8^\circ$ are displayed in the outer ring according to their $l$ and $b$, with the same convention of RM symbols and limits. The data from the NVSS RM catalog (Taylor et al. 2009) are plotted in light-blue and pink symbols. The large-scale structure of magnetic fields in the Galactic disk, as indicated by arrows, are derived from the distribution of pulsar RMs and the comparison of pulsar RMs with the RMs of background EGRs.

The intrinsic Faraday rotation from the emission region and pulsar magnetosphere (Wang et al. 2011). For a pulsar at distance $D$ (in pc), the RM is given by $RM = 0.810 \int_0^D n_e B \cdot dl$. With the pulsar dispersion measure, $DM = \int_0^D n_e dl$, we obtain a direct estimate of the field strength weighted by the local free electron density

$$\langle B_\parallel \rangle = \frac{\int_0^D n_e B \cdot dl}{\int_0^D n_e dl} = 1.232 \frac{RM}{DM}.$$  

(3.1)
Pulsars as probes for the Galactic magnetic fields

Pulsars are spread through the Galaxy at approximately known distances, allowing three-dimensional mapping of the magnetic fields. If pulsar RM data are model-fitted with the magnetic field structures with the electron density model (Han & Qiao 1994), then the pulsars and EGRs are more or less equivalently good as probes for the magnetic structure. But when RM and DM data are available for many pulsars in a given region with similar lines of sight, e.g., one pulsar at $d_0$ and one at $d_1$, the RM change against distance or DM can indicate the direction and magnitude of the large-scale field in particular regions of the Galaxy (Han et al. 1999, 2002, 2006). Field strengths in the region can be directly derived by using

$$\langle B_{||}\rangle_{d_1-d_0} = 1.232 \frac{\Delta RM}{\Delta DM}, \quad (3.2)$$

where $\langle B_{||}\rangle_{d_1-d_0}$ is the mean line-of-sight field component in $\mu$G for the region between distances $d_0$ and $d_1$, $\Delta RM = RM_{d_1} - RM_{d_0}$ and $\Delta DM = DM_{d_1} - DM_{d_0}$. Notice that this derived field is not dependent on the electron density model.

As shown in Han et al. (2006), the available pulsar RM data show that magnetic fields in the spiral arms (i.e., the Norma arm, the Scutum and Crux arm, and the Sagittarius and Carina arm) are always counterclockwise in both the first and fourth quadrants, though some disordered fields appear in some segments of some arms. At least in the local region and in the fourth quadrant, there is good evidence that the fields in interarm regions are similarly coherent, but reversed to be clockwise. Therefore at least four or five reversals in the fourth quadrant occur from the centre to the outskirts of our Milky Way. In the central Galactic region interior to the Norma arm, new RM data of pulsars indicate that the fields are clockwise, reversed again from the counterclockwise field in the Norma arm. In the first Galactic quadrant, because the separations between spiral arms are so small, the RM data are dominated by counterclockwise fields in the arm regions though a few negative pulsar RMs indicate clockwise fields in the interarm regions.

We notice that the averaged variation of RMs of extragalactic radio sources along the Galactic longitudes (Brown et al. 2007) are consistent with the field reversal pattern obtained from pulsar RMs.

Using pulsar RM and DM data, Han et al. (2006) were able to measure the strength of regular azimuthal fields near the tangential regions in the 1st and 4th Galactic quadrants. Although the “uncertainties”, which in fact reflect the random fields, are large, the tendency is clear that fields get stronger at smaller Galactocentric radius and weaker in interarm regions. The radial variation is,

$$B_{\text{reg}}(R) = B_0 \exp \left[ -\frac{(R - R_\odot)}{R_B} \right], \quad (3.3)$$

with the strength of the large-scale field at the Sun, $B_0 = 2.1 \pm 0.3 \mu$G, and the scale radius $R_B = 8.5 \pm 4.7$ kpc, $R$ is the distance from the Galactic center, $R_\odot = 8.5$ kpc is the galactocentric distance of the Sun.

Pulsar RMs have also been used to study the small-scale random magnetic fields in the Galaxy. Some pairs of pulsars close in sky position have similar DMs but very different RMs, indicating an irregular field structure on scales of about 100 pc. Some of these irregularities may result from HII regions in the line of sight to a pulsar (Mitra et al. 2003). It has been found from pulsar RMs that the random field has a strength of $B_r \sim 4 - 6 \mu$G independent of cell-size in the scale range of 10 – 100 pc. From pulsar RMs in a very large region of the Galactic disk, Han et al. (2004) obtained a power law distribution for magnetic field fluctuations of $E_B(k) = C \ (k/\text{kpc}^{-1})^{-0.37\pm0.10}$ at scales from $1/k = 0.5$ kpc to 15 kpc, with $C = (6.8 \pm 0.8) \times 10^{-15}$ erg cm$^{-3}$ kpc, corresponding to an rms field of $\sim 6\mu$G in the scale range.
4. Conclusions and discussions

Pulsars are excellent probes of the magnetic fields in our Milky Way. They are the best to reveal the magnetic field structure in the Galactic disk, especially the field reversals; they are the best to derive the magnetic field strength — much less model-dependent than other probes; and they are the best to get the observational spatial energy spectrum of the magnetic fields. Pulsars can also be used to probe the magnetic fields in the Galactic halo. We already have RMs for about half of the known pulsars and these have been used for studies of the Galactic magnetic fields. In the future, when more and more known pulsars are observed for their rotation measures, we can get more details of magnetic structure in the nearby half of the Galactic disk.

Note that magnetic fields in the Galactic disk of the far side of the Galactic center are not yet explored; very few distant pulsars have been found there. When more and more pulsars are discovered in the far half of the disk, using FAST and SKA, for example, we can study the differences in RMs and DMs of pulsars at various distances in different arms, and measure the magnetic field directions and strength in the remote arms, so that the global structure of the disk fields can be well revealed. However, if the large-scale magnetic fields always go along arms, as present data suggest, the RMs of distant pulsars will become less sensitive to the magnetic fields in the far half disk because the lines of sight will be more perpendicular to the spiral arms than in the nearby half. The distribution of the magnetic fields of OH masers in HII and star formation regions can always be used as supplementary tools for large-scale magnetic fields (Han & Zhang 2007), if the large-scale fields of the large-scales are somehow “remembered” in clouds or clumps of small scales as currently available data suggested.

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References

Pilot pulsar surveys with LOFAR

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on behalf of the LOFAR Pulsar Working Group

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Abstract. We are performing two complementary pilot pulsar surveys as part of LOFAR commissioning. The LOFAR Pilot Pulsar Survey (LPPS) is a shallow all-sky survey using an incoherent combination of LOFAR stations. The LOFAR Tied-Array Survey (LOTAS) is a deeper pilot survey using 19 simultaneous tied-array beams. These will inform a forthcoming deep survey of the entire northern hemisphere, which is expected to discover hundreds of pulsars. Here we present early results from LPPS and LOTAS, among which are two independent pulsar discoveries.

Keywords. stars: neutron, pulsars: general, surveys

1. Introduction

The Low Frequency Array (LOFAR) is a radio telescope under construction in Western Europe (van Haarlem et al. in prep.). LOFAR’s core is in the province of Drenthe, The Netherlands. It operates in two bands, a low band (10 – 90 MHz) and a high band (110 – 250 MHz), each with its own type of antenna. These bands cover the lowest 4 octaves of the radio window. LOFAR is a phased array consisting of many relatively inexpensive antennas, whose signals are digitized and then processed mostly in software. The antennas are grouped in stations where each station is the equivalent of a steerable dish in a traditional interferometer. LOFAR will consist of 40 Dutch stations and 8 international stations (in France, Germany, Sweden and the United Kingdom). All of the core and international stations are complete, and more than half of the remote Dutch stations are also operational. The same software correlator allows LOFAR to operate in both imaging and beam-formed modes. Each beam in the beam-formed mode is synthesized by adding data from multiple stations and acts as the field-of-view of a single-dish telescope. This mode provides the high time resolution required for pulsar survey observations (Stappers et al. 2011). The number of beams that LOFAR can create simultaneously is only constrained by compute power and system throughput, but can be as high as several hundreds, covering up to hundreds of square degrees. In the low band these beams can be pointed anywhere on the sky in the high band they need to be clustered.

Low-frequency observations of pulsars are complicated by 3 effects: dispersion, scattering and higher sky background temperature. Dispersion, the delay caused by free electrons in the interstellar medium (ISM), smears out pulsar signals thus making them less detectable. Since the delay scales with frequency $\nu$ as $\nu^{-2}$, LOFAR observations are strongly affected. Fortunately, the availability of abundant compute power allows incoherent de-dispersion with small channel bandwidths, or even online coherent de-dispersion for up to 40 different trial dispersion measures†. Scattering caused by multipath propagation in the clumpy ISM is highly dependent on the line-of-sight, and scales as $\nu^{-4.4}$.†

† Intermediate dispersion measure trials can be filled in with offline incoherent de-dispersion.
Figure 1. Three LOFAR high-band sub-stations in LPPS mode, where they each create 7 beams of 6.8 MHz bandwidth each. Since each station is pointed in the same direction, LOFAR’s central correlator can incoherently combine the station beams. This maintains the large station beam field-of-view, about 75 square degrees for LPPS, whilst increasing the overall sensitivity with square root of the number of substations added. The LPPS survey used up to 44 substations per observation.

It cannot be easily corrected for. This is a problem especially for pulsar observations in the Galactic plane. Conversely, because LOFAR is more strongly affected by scattering, it is an instrument well suited to studying the structure of the ISM with pulsars. Finally, the background sky temperature increases with decreasing observing frequency, as $\nu^{-2.6}$. This effect is mostly a problem towards the Galactic plane. Fortunately, two properties of pulsars potentially increase the chance of a LOFAR detection. Their spectrum generally goes as $\nu^{-1.8}$ and their beams are broader at low frequencies.

LOFAR is an efficient pulsar surveying instrument. LOFAR’s antenna elements are sensitive to a large part of the sky, and the correlator can create many beams with a combined field-of-view of tens to hundreds of degrees. Therefore, LOFAR can cover a large part of the sky in little observing time, and/or use long dwell times. The beam-forming can happen in two modes: station data can be combined either coherently or incoherently. The coherent mode offers maximum raw sensitivity, while the incoherent mode trades sensitivity for larger field-of-view; see van Leeuwen & Stappers (2010) for the details of this trade-off. During LOFAR commissioning the LOFAR Pulsar Working Group performed pilot surveys in each of these modes. The first such survey, the LOFAR Pilot Pulsar Survey (LPPS), used incoherent addition of 7 beams created at station level. The second survey, the LOFAR Tied Array Survey (LOTAS), exercised the ability to create 19 tied-array beams by coherently adding station data.

In Section 2 we give an overview of the LPPS survey and present some recent results. In Section 3 we do the same for the LOTAS survey and finally in Section 4 we discuss the lessons learned and the future outlook for pulsar surveys with LOFAR.

2. The LOFAR Pilot Pulsar Survey

The LPPS survey was started almost as soon as LOFAR gained the ability to form several beams at station level and combine those beams for all stations at the central correlator. The observations were taken in December 2010 and early January 2011. Each
LPPS pointing had 7 beams with 6.8 MHz bandwidth, a sampling time of 0.65 ms and a dwell time of 57 minutes. This long dwell time was possible because each pointing covered about 75 square degrees (see Figure 1). LPPS is comprised of about 250 such observations. The search processing is now complete, and candidate inspection is in progress.

The search was performed with a custom Python pipeline using tools from the PRESTO (Ransom 2001) pulsar data reduction package. The data were reduced at ASTRON and the University of Manchester. We searched the data for both periodicities and single dispersed pulses. In Figure 2 we present an interesting single-pulse detection of PSR J0240+62, a recently discovered pulsar with a low dispersion measure (DM) of $\sim 4$ (Hessels et al. 2008). This shows that LOFAR has the outstanding ability to detect low-DM sources. The periodicity search yielded the first independent† discovery of a pulsar, PSR J2317+68, with LOFAR (see the left panel of Figure 3).

3. The LOFAR Tied Array Survey

LOTAS, the second pulsar commissioning survey, was set up to test the ability to create multiple tied-array beams for surveying. For this survey, we used the 6 inner-most stations to create 19 beams, each with LOFAR’s full bandwidth of 48 MHz. The observations were 17 minutes each with a sampling time of 1.3 ms. Since these 6 stations act as one large, single station the beams cover approximately 3.7 square degrees total, a smaller area than those for the LPPS survey. For LOTAS we observed about 200 pointings.

The data reduction for this survey is being performed with an updated version of the LPPS data reduction pipeline, running at The University of Manchester and at the SARA Grid Node in Amsterdam. The LOTAS survey has so far yielded the second, again independent‡, discovery of a pulsar, PSR J2243+69 (see the right panel of Figure 3).

† Only weeks before, the GBNCC pulsar survey had discovered this pulsar (priv. comm.).
‡ This pulsar has also been discovered recently by the GBNCC survey (priv. comm.).
Figure 3. The two independent discoveries in the LOFAR pulsar commissioning surveys. On the left PSR J2317+68, found in the LPPS data; on the right PSR J2243+69, found in LOTAS.

4. Discussion and further work

The independent discovery of two pulsars in LOFAR’s pulsar commissioning surveys shows that LOFAR is already competitive for such work. It needs to be emphasized that the LPPS survey used LOFAR in a very early stage when it was not yet fully calibrated. The data processing for the LPPS and LOTAS surveys is not yet complete and we expect that these surveys will yield more discoveries soon. For LPPS we are wrapping up the processing and inspecting the results. Because of the large field-of-view × time on sky we aim to derive a limit on the rate of bright radio bursts, in the absence of strong scattering constraints.

LOFAR’s capabilities are still being extended. For targeted observations it will increase because the central single clock will be rolled out beyond the inner-most 6 stations, connecting a total of 24 core stations by the end of 2012 — providing a 4-fold increase in raw sensitivity. Better usage of the available network bandwidth is expected to increase the observing bandwidth to 80 MHz. Monitoring of the individual stations’ data quality and a better understanding of the interference environment will further increase the data quality compared to that of our early surveys.

Now that LOFAR is emerging from its commissioning period, the LOFAR Pulsar Working Group is gearing up to perform a deeper survey of the northern celestial hemisphere. This survey, the LOFAR Tied Array All-Sky survey (LOTAAS), will use 61 tied-array beams formed with only the 6 inner-most stations. A move to using all core stations would increase raw-sensitivity by a factor 4 over this setup. The decrease in field-of-view, however, cannot be compensated for by creating more beams (as the computing and storage requirements exceed what is available currently or in the near future). With a sampling time of 164 µs LOTAAS, unlike LPPS and LOTAS, is designed to be sensitive to both regular and millisecond pulsars.

References
FRATs: Searching for fast radio transient in real-time with LOFAR

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Abstract. LOFAR is an innovative new radio interferometer operating at low radio frequencies from 10 to 270 MHz. It combines a large field-of-view, high fractional bandwidth, rapid response, and a wide range of baselines from tens of meters to thousand kilometers. Its use of phased-array technology and its digital nature make LOFAR an extremely versatile instrument to search for transient radio phenomena on all time scales. Here we discuss in particular the search for fast radio transients (FRATs) at sub-second time scales. In fact, at these time scales the radio sky is rather dynamic due to coherent emission processes. Objects like pulsars, flaring stars, or planets like Jupiter are able to produce bright short flares. For pulsars, most previous detection strategies made use of the rotation of pulsars to detect them, using Fourier techniques, but it is also possible to detect pulsars and other objects through their single pulses. Such surveys have, e.g., led in the previous decade to the detection of Rapid Radio Transients (RRATS), but the unprobed search space is still rather large. LOFAR is now conducting a rather unique survey over the entire northern sky, searching for bright dispersed single radio pulses. This FRATs survey makes use of the LOFAR transient buffer boards (TBBs), which had initially been used to detect nanosecond radio pulses from cosmic rays. The TBBs store the radio data from each single receiver element of LOFAR and allow one to look back in time. A trigger system that runs parallel to normal imaging observation allows one to detect single pulses in an incoherent beam of all LOFAR stations, covering several tens to hundred square degrees at once. Once triggered, the data can be used to localize the pulse and to discriminate cosmic sources from terrestrial interference through 3D localization. The system has been successfully tested with known pulsars and first results of the ongoing survey will be presented.
Session 10

Galactic distribution and

evolution of neutron stars
The Galactic Millisecond Pulsar Population

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Abstract.
Among the current sample of over 2000 radio pulsars known primarily in the disk of our Galaxy, millisecond pulsars now number almost 200†. Due to the phenomenal success of blind surveys of the Galactic field, and targeted searches of Fermi gamma-ray sources, for the first time in over a decade, Galactic millisecond pulsars now outnumber their counterparts in globular clusters! In this paper, I briefly review earlier results from studies of the Galactic millisecond pulsar population and present new constraints based on a sample of 60 millisecond pulsars discovered by 20 cm Parkes multibeam surveys. I present a simple model of the population containing ∼30,000 potentially observable millisecond pulsars with a luminosity function, radial distribution and scale height that matches the observed sample of objects. This study represents only a first step towards a more complete understanding of the parent population of millisecond pulsars in the Galaxy and I conclude with some suggestions for further study in this area.

Keywords. stars — neutron; methods – statistical

1. Introduction
Millisecond pulsars have been the subject of intense discovery over the past few years. Thanks to the current generation of large-scale pulsar surveys, we find ourselves in an era where we have large samples of both millisecond and normal pulsars and, in particular for millisecond pulsars, there are many opportunities to learn about the population of objects as a whole based upon the ones we see. The contributions by Keith, Ng, Lazarus and Lynch elsewhere in these proceedings provide the latest status of these searches, and further details can be found in Lorimer (2011). These discoveries are due to the modern surveys having low-noise receiver systems with a large fractional bandwidth and employing state-of-the-art digital data acquisition systems which are now close to optimal (e.g. DuPlain et al. 2008), as well as substantial computing resources using sophisticated search processing algorithms which can largely remove radio-frequency interference and combat the effects of binary motion during the observation. In addition, multiple analyses of the data often result in additional discoveries (e.g. Keith et al. 2009; Eatough et al. 2010; Mickaliger et al. 2012).

Along with the current generation of ongoing pulsar surveys at Green Bank, Parkes, Arecibo and Effelsberg, a key set of surveys that provide the backbone for much of the current population analyses are the Parkes multibeam surveys. These groundbreaking experiments were carried out using analog filterbanks and had substantially better sensitivity to millisecond pulsars compared to previous efforts. The main surveys of interest here are the Galactic plane survey (Manchester et al. 2001), the Swinburne intermediate (Edwards et al. 2001) and high-latitude (Jacoby et al. 2009) pulsar surveys, the high latitude survey (Burgay et al. 2006) and Perseus arm survey (Burgay et al. 2012) as well as

† For my list of Galactic millisecond pulsars, see http://astro.phys.wvu.edu/GalacticMSPs
a deep multibeam survey of the northern Galactic plane (Lorimer, Camilo & McLaughlin 2013). In spite of their good sensitivity, these surveys were ultimately limited by a number of selection effects which bias their pulsar samples and need to be accounted for by population analyses. These selection effects include the inverse-square law, pulse dispersion and scattering, pulsar intermittency, interstellar scintillation and also binary motion. For further details of these effects, the interested reader is referred to earlier reviews on this subject (Lorimer 2009, 2011).

2. Overview of modeling approaches

Although early efforts to correct for observational selection were done via analytical treatments (e.g. Gunn & Ostriker 1970), nowadays this is best done in a Monte Carlo fashion to create realizations of the true of the underlying pulsar population which are then searched using models of survey detection thresholds which account for propagation in the interstellar medium. The contribution by Cordes in this volume describes current work to update the so-called “NE2001” electron density model (Cordes & Lazio 2002) which is currently used to model the propagation effects in these population syntheses. The reader is also referred to recent work on this subject by Schnitzeler (2012).

From statistical analyses of samples of artificial pulsars that satisfy the criteria for detection, it is possible to generate and optimize models for the pulsar population which inform us about the underlying distribution functions and make predictions for future survey yields. Although a variety of different approaches have been employed, the Monte Carlo simulations follow two basic strategies. In the “snapshot” approach, no assumptions are made concerning the prior evolution of pulsars. Instead, the populations are simply generated according to various distribution functions (typically in Galactocentric radius, $R$, height with respect to the plane, $z$, spin period, $P$ and luminosity, $L$) which are optimized in order to find the best match to the sample. Alternatively, one may carry out “evolution” approaches where the model pulsars are evolved forward in time from a set of initial distributions. Software to carry out both approaches has been developed by a number of groups and some of this is freely available†.

The snapshot approach was applied to the normal pulsar population by Lorimer et al. (2006) who were able to derive best-fitting probability density functions in $R$, $L$, $z$ and $P$ for the present-day population of objects. One result of this work was that the radial distribution of pulsars could not be decoupled from the radial distribution of free electrons in the pulsar distribution. For the evolution approach on the normal population, the current state-of-the-art is the work of Faucher-Giguère & Kaspi (2006) who generated excellent fits to the pulsar $P$-$\dot{P}$ diagram using a model in which the luminosity has a power-law dependence on $P$ and $\dot{P}$. In their optimal model, $L$ scales as $P^{-1.5} \dot{P}^{0.5}$, i.e. the square root of the spin-down luminosity. One interesting result from this paper is that the luminosity function of the present-day pulsar population appears to be log-normal in form. The smooth tails of this distribution (which are integrable over all luminosities to give a finite result) offer a distinct advantage over previous studies which parameterized the luminosity as a power law which is divergent and requires a somewhat unphysical minimum luminosity. Similar results were found by Ridley & Lorimer (2010). The log-normal form of the luminosity distribution has subsequently been adopted as a starting point by a number of other studies (e.g., Boyles et al. 2011; Bagchi et al. 2011 and Chennamangalam et al. 2012; see also these proceedings).

† For example, the psrcpop software package at http://psrpop.phys.wvu.edu has modules to carry out both the snapshot and evolution approaches
3. Previous studies of the millisecond pulsar population

One of the first efforts to quantify the millisecond pulsar population was the work of Kulkarni & Narayan (1988) who used a $V/V_{\text{max}}$ approach to estimate the number of similar objects to those observed by surveys at that time. With a sample of only three millisecond pulsars, their study was subject to large uncertainties, but it began a significant discussion on the so-called “birthrate problem” for millisecond pulsars. Based on their results Kulkarni & Narayan (1989) claimed that the birthrate of millisecond pulsars was substantially greater than that of their proposed progenitors, the low-mass X-ray binaries. This problem has largely disappeared as better constraints have become available from larger samples (Lorimer 2009). Rathnasree (1993) attempted to synthesize the population of millisecond pulsars from low-mass X-ray binaries by carrying out Monte Carlo simulations to model their evolution since birth. The current state of the art of this approach is discussed in the contribution by Tauris in this proceedings.

A prescient paper by Johnston & Bailes (1991) demonstrated that the local population of millisecond pulsars revealed by all-sky surveys at $\sim 0.4$ GHz should be largely isotropic. This work, and early discoveries of two recycled radio pulsars at high Galactic latitudes (Wolszczan 1990) inspired a number of 400 MHz pulsar surveys during the 1990s which led to a sample of about 30 objects at the end of the decade. During that time, studies of the scale height, velocity distribution and luminosity function were performed (Lorimer 1995; Cordes & Chernoff 1997; Lyne et al. 1998) and it was found that the local (within a few kpc) millisecond pulsar population potentially observable was comparable in size to the equivalent population of normal pulsars. One conclusion from these studies is that the populations of millisecond and normal pulsars are consistent with a single velocity distribution applied to all neutron stars at birth (Tauris & Bailes 1996).

4. A new analysis of the millisecond pulsar population

We are now in an era where significant further understanding of the millisecond pulsar population should be possible in the coming years. As a starting point, I present here a snapshot analysis of the sample of millisecond pulsars detectable by the Parkes multibeam surveys prior to the current high time-resolution universe surveys (see Keith’s contribution in this proceedings, and Keith et al. 2010). The total number of millisecond pulsars from these surveys now numbers 58. This number turns out to have more-or-less asymptoted, but may still increase further thanks to a number of new discoveries† by reanalyses of the Parkes multibeam survey of the Galactic plane.

Using the snapshot approach, I have developed a model (hereafter referred to as model A) which has the following parameters: (i) a log-normal luminosity function with an identical mean and standard deviation (i.e. $-1.1$ and $0.9$) to that found by Faucher-Giguère & Kaspi (2006). This function was found to be consistent with recycled pulsars in globular clusters recently by Bagchi et al. (2012); (ii) a manually-tweaked period distribution with a peak at 3 ms; (iii) an exponential scale height with a mean of 500 pc; (iv) a Gaussian radial distribution with a standard deviation of 7.5 kpc. The period distribution was arrived at by initially choosing periods from a distribution which is uniform in log $P$ between 1 and 30 ms. I adjusted the relative weighting of the bins to arrive at a distribution which most closely matches the observed sample. The $z$ distribution was motivated by my earlier results (Lorimer 1995) based on the low-frequency surveys.

† Data analysis by the Einstein@Home team has so far discovered 23 sources including one highly dispersed millisecond pulsar, while Mickaliger et al. (2012) have recently announced the discovery of five further millisecond pulsars.
Figure 1. The sample of millisecond pulsars detected in the five major surveys (top panels) confronted with the equivalent distributions from model A shown in the lower panels (see text).

Table 1. Summary of the simulation results obtained from our snapshot modeling of the millisecond pulsar population. From left to right we list the model, base-10 logarithm of the combined Kolmogorov Smirnoff probability ($Q_{KS}$), the reduced chi-squared value ($\chi^2_{\text{nobs}}$) and the number of potentially observable millisecond pulsars in the Galaxy ($N_{\text{Galaxy}}$).

As can be seen in Fig. 1, this model provides a reasonable match to the observed sample. I define reasonable in this context in terms of a comparison of the observed and predicted survey yields and also by looking at the observed distributions of spin period, $P$, dispersion measure, DM, Galactic longitude, $l$, and Galactic latitude, $b$. In Table 1, along with the total number of potentially observable pulsars I tabulate two figures of merit for this model: $Q_{KS}$ and $\chi^2_{\text{nobs}}$. The former is the base 10 logarithm of the product of the four individual Kolmogorov-Smirnoff (KS) tests between $P$, DM, $l$ and $b$. The latter is the reduced $\chi^2$ computed from the observed and predicted numbers of pulsars.

Also listed in the Table are the equivalent numbers for a number of other models B–I. The approach I took here was to investigate the impact of each assumption made in

‡ These are the number of pulsars in the model Galaxy whose beams intersect our line of sight — i.e. uncorrected for beaming effects.
model A by changing it, but keeping all other assumptions constant. In model B, to show
the impact on the choice of luminosity function on the results, I made only a small change
to mean of the log-normal function, i.e. –1.1 to –1.2. The figures of merit are comparable
to model A, but the number of pulsars increases by about 14%. For model B, to show
that the sample does require a radial dependence on number density, I generated pulsars
assuming constant number density on the plane throughout the model galaxy. Here,
both figures of merit are substantially poorer due to the gain in number of detections at
higher Galactic longitudes. The number of pulsars required in the model is substantially
reduced, since it is now much easier to detect the population at larger $R$. Models G and
H, where the scale length is varied by ±1 kpc from the value in model A show that our
ability to constrain the scale length is currently not very good. In model D, I adopt the
Cordes & Chernoff (1997) spin period distribution. Although the relative survey yields
are satisfactory, this distribution predicts a substantial fraction of millisecond pulsars
with $P < 2$ ms which is much higher than that observed. A similar result is found using
a Gaussian period distribution (model I) with a mean of zero and a standard deviation
of 10 ms†. Reducing the scale height of the population in model E to 100 pc substantially
worsens the agreement with the observed data, while increasing the scale height to 1 kpc
(model F) has less of an effect.

5. Suggestions for further work
The analysis presented here will be described further in a forthcoming Parkes multi-
beam survey paper. It represents a first step towards a more detailed understanding of
the millisecond pulsar population in the Galaxy. Further work is encouraged to account
for the following subtleties not included here. Of particular interest are studies of the
motion of millisecond pulsars in the $P – \dot{P}$ diagram and the relationship to the low-
mass X-ray binary population. The work of Kiziltan & Thorsett (2010) and Tauris et
al. (2012) relates directly to the first issue. Further work in this area, along the lines of
the population syntheses carried out by Story et al. (2007) seem to be the next logical
step. Significant progress is now being made in modeling the binary evolutionary steps
and predicting distributions for orbital parameters for the binary population (see, for
example, Belszcynski et al. 2008). Combining all these elements into an all-encompassing
synthesis of the millisecond pulsar population which accounts (as far as possible) for the
observational selection effects is now a major goal of future studies. On the road to such
a lofty goal, past experience with the normal pulsar population (see, for example, Lorimer
2009) suggests that it will be extremely profitable to break up the steps into a number of
smaller problems. One such example is the radio-selected sample of millisecond pulsars
revealed by Fermi (Ray et al. 2012). A careful study of the selection effects impacting
this sample should now be undertaken in order to fully understand the impact of these
discoveries on our knowledge of the millisecond pulsar population.

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† Only the positive periods from this distribution are used for this model!
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Discussion

Keane: Pulsar surveys are not exhaustively searched. Is there any means to account for this in your modeling?

Lorimer: There is a “fractional completeness” parameter in PSRPOP that can be tweaked.

Ransom: We heard earlier in the week for millisecond pulsars that there might be some interesting spectral dependencies. How easy would it be to add in the larger 350 MHz surveys into this modeling?

Lorimer: Not too difficult. We just need the information describing the sky coverage of these surveys. What you then need to do is to add the pulsar spectra to your models, but that will hopefully teach you something about that. [Note added in write-up: see the contribution by Youling You et al. in these proceedings]

Heras: For the 20% of millisecond pulsars which are isolated, are there any differences between this population and those that are members of binary systems?

Lorimer: As far as I am aware (and I looked at this last a few years ago), there are no significant differences in the population of isolated or binary millisecond pulsars in terms of \( P \), \( L \), spatial distribution etc. What I think is interesting is whether the binary population syntheses can match that 20% isolated millisecond fraction that we currently observe. That remains to be seen.
The pulsar population in Globular Clusters and in the Galaxy

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Abstract. In this paper, I review some of the basic properties of the pulsar population in globular clusters (GCs) and compare it with the the Galactic disk population. The neutron stars (NSs) in GCs were likely formed - and appear to continue forming - in highly symmetric supernovae (SNe), likely from accretion-induced collapse (AIC). I review the many pulsar finds and discuss some particularly well populated GCs and why they are so. I then discuss some particularly interesting objects, like millisecond pulsars (MSPs) with eccentric orbits, which were heavily perturbed by passing stars. Some of these systems, like NGC 1851A and NGC 6544B, are almost certainly the result of exchange interactions, i.e., they are witnesses to the very same processes that created the large population of MSPs in the first place. I also review briefly the problem posed by the presence of young pulsars in GCs (with a special emphasis on a sub-class of young pulsars, the super-energetic MSPs), which suggest continuing formation of NSs in low-velocity SNe. In the final section, I discuss the possibility of an analogous population in the Galaxy and highlight a particularly interesting case, PSR J1903+0327, where the primary neutron star appears to have formed with a small-velocity kick and small fractional mass loss. Systems with primary NSs formed in electron-capture SNe should constitute a distinct low-velocity Galactic population akin in many respects to the GC population. Current high-resolution surveys of the Galactic plane should be able to detect it clearly.

Keywords. (Galaxy:) globular clusters: general, stars: neutron, (stars:) pulsars: general, X-rays: binaries, (stars:) binaries: eclipsing

1. The Pulsar population in Globular Clusters

Globular clusters (GCs) are spherical, bound swarms of stars containing from $10^4$ to $\sim 5 \times 10^6$ stars. Near their centers the star density is normally over $10^3$ (and in some cases $10^6$!) per cubic parsec. They orbit the centers of most Galaxies through the Universe, about 200 orbit our Milky Way (Harris 1996). Of these, 28 clusters contain a total of 144 known radio pulsars†.

The GC pulsar population differs from the Galactic disk population in two main ways:

(a) It is much older than the Galactic population. This is to be expected given the great age of the stellar population in GCs. This population is so old that, with a few important exceptions (discussed below), only recycled pulsars, which have lifetimes of many Gyr, are still detectable as radio pulsars.

(b) It is a very abundant population. Per unit mass there appear to be two to three orders of magnitude more pulsars in GCs as in the Galactic disk. This also applies to X-ray sources, the progenitors of MSPs.

The reasons for this latter fact, and its many consequences, are discussed in detail below.

† Our updated reference list is at http://www.naic.edu/~pfreire/GCpsr.html

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2. Large neutron star population in globular clusters

2.1. Exchange encounters

In the early 1970’s, the Uhuru and OSO-7 X-ray satellites revealed the presence of several X-ray sources in GCs (e.g. Giacconi et al. 1974). One of the co-authors (H. Gursky) recognized in 1973 that, compared to the stellar mass in the Galaxy, this represented a large overabundance of X-ray sources. In 1975 G. Clark suggested that, given the extremely high stellar densities in the cores of some GCs, it occasionally happens that many old, dead NSs lurking in the core “collide” with a binary, disrupt it and acquire a (new) companion. The latter then evolves, fills its Roche lobe and starts transferring matter to the NS, forming a low-mass X-ray binary (LMXB).

2.2. Origin of large NS population

An important question already considered in these early studies is the origin of all these lurking NSs. In the early 1970’s some pulsar proper motions had already been measured (e.g., Manchester et al. 1974) and these already hinted at the fact that many NSs form with kick velocities of hundreds of km per second. This has since been confirmed by many subsequent studies, with ever-increasing samples and better quality measurements (Lyne & Lorimer 1994, Hobbs et al. 2005). Such objects would not be retained in GCs, which have escape velocities of a few tens of km s\(^{-1}\) unless they are anchored by massive companions (Davies & Hansen 1998). Even with such anchoring, there seems to be a large excess of NSs (Pfahl, Rappaport & Podsiadlowski 2002), which lead to a suggestion, still valid (originally by Katz 1975) that NSs in GCs are forming through a low-velocity channel. This is now thought (Podsiadlowski et al. 2004) to be accretion-induced collapse (AIC) of massive Oxygen-Neon-Magnesium WDs that become unstable once they approach the Chandrasekhar limit. This results in electron capture SNe (Poelarends et al. 2008, Langer 2012), not Type 1a SNe — there is not enough carbon available to power thermonuclear deflagrations. We will come back to this issue later.

3. Millisecond pulsars - in the Galaxy and in GCs

Soon after the discovery of the first MSP, B1937+21 in 1982 (Backer et al. 1982), it was suggested that MSPs are the end stages of the evolution of LMXBs (Alpar et al. 1982). This is consistent with the finding that, unlike in the case of normal pulsars, most MSPs are found in binary systems. Here the mystery is why some of these objects (including B1937+21 itself) are found to be isolated; there is no satisfactory answer to this question yet. Furthermore, MSPs have magnetic fields much smaller than those generally found in the normal pulsar population; which means that accretion somehow “buries” the magnetic field. This process is not well understood.

If MSPs really evolve from LMXBs, then GCs, with their LMXB over-abundance, should also contain many MSPs. Finding them was difficult, given the great distances to GCs. Nevertheless, if a bright radio source is discovered in a GC, then it is likely a pulsar. In 1985, twelve nearby GCs were imaged with the Very Large Array (VLA, Hamilton, Helfand & Becker 1985), with one likely candidate in M28, B1821−24. Two years later, using the Jodrell Bank 75-m radio telescope, the discovery of radio pulsations at a period of 3.05 ms and DM of 120 cm\(^{-3}\)pc confirmed it as the first pulsar in a GC (Lyne et al. 1987). In the following year, PSR B1620−26 is discovered in the globular cluster M4 (Lyne et al. 1988). This pulsar, with a spin period of 11 ms, is in a 191-day orbit with a white dwarf (WD). Interestingly, this binary system appears to be orbited by a Jovian-type planet in a very wide orbit (Sigurdsson et al. 2003).
3.1. Finding more

The pulsars in GCs are faint owing to their great distances. This means that we are limited first and foremost by the sensitivity of the radio telescope and receiver used for the survey. This can be, to some extent, compensated by the fact that the pulsars are located in a small region around the cluster center (owing to the effects of mass segregation, see e.g., Freire et al. 2001a) which normally fits very well inside a single radio beam of even the largest radio telescopes. This allows for deep, multi-hour search observations, which can still be made sensitive to binary pulsars using acceleration search techniques (Camilo et al. 2000, Ransom et al. 2002). This is the reason why for most of the last 20 years we knew more MSPs in clusters than in the Galactic disk.

3.2. Notable clusters and why they are so

The early leader in pulsar discoveries was 47 Tucanae (Manchester et al. 1990, Manchester et al. 1991, Robinson et al. 1995, Camilo et al. 2000), which now has a total of 23 known pulsars, all of them with spin periods shorter than 7.6 ms. Of these, 15 are in binary systems, at least five of them eclipsing. The timing of these pulsars (Freire et al. 2001a) allowed X-ray detections of all of the MSPs (Heinke et al. 2005, Bogdanov et al. 2006), a study of the dynamics of the cluster (Freire et al. 2003) and the first detection of any sort of interstellar medium in a globular cluster, after more than 60 years of searches (Freire et al. 2001b).

However, radio maps of a large group of GCs (Fruchter & Goss 2000) suggested that the heavily obscured GC Terzan 5 had a large pulsar population, but of these only two were known before that study (Lyne et al. 1990, Lyne et al. 2000). Sensitive observations at 2 GHz with the GBT have since discovered 32 pulsars (Ransom et al. 2005, Hessels et al. 2006). These include Terzan 5 ad (Hessels et al. 2006): with a spin frequency of 716 Hz; this broke the 24-year old record set by the original MSP, B1937+21. It is thought that ~100 pulsars remain to be discovered in Terzan 5 (Bagchi, Lorimer & Chennamangalam 2011).

Using the same observing system 8 new pulsars were found in NGC 6440 and NGC 6441 (Freire et al. 2008a) and 11 new pulsars in M28 alone! Freire et al. (2008a) found that, for any particular luminosity threshold, there are nearly as many pulsars in NGC 6440 and NGC 6441 as there are in Terzan 5. The latter appears to be exceptional because of its smaller distance to the Solar System (5.5 kpc), as opposed to 8.2 kpc for NGC 6440 and 13.5 kpc for NGC 6441. This results highlights the fact that these surveys are strongly limited by sensitivity.

It is nevertheless clear that, after correcting for distance, some GCs have many more pulsars than the average. Although we don’t know all the factors involved in producing a large pulsar population, the stellar encounter rate has some predictive power not only in estimating the number of MSPs, but of other types of objects (e.g., Davies 1995), particularly X-ray binaries (e.g., Pooley et al. 2003).

3.3. Clusters with isolated pulsars

The pulsar populations of some clusters [NGC 7078 (Anderson 1993), NGC 6624 (Biggs et al. 1994, Lynch et al. 2012), NGC 6517 (Lynch et al. 2011) and NGC 6752 (D’Amico et al. 2001, D’Amico et al. 2002)] are dominated by isolated pulsars, while others [like 47 Tuc (Camilo et al. 2000), M62 (Possenti et al. 2003, Lynch et al. 2012), M3, M5 and M13 (Kulkarni et al. 1991, Anderson et al. 1997, Hessels et al. 2007)] are dominated by binaries. The distinguishing characteristic appears to be the core density; most of the GCs where there are more isolated pulsars appear to be core collapsed. The high stellar density at the core might be disrupting previously formed binary MSPs. Another possible
disrupter are central black hole binaries, as has been suggested in the case of NGC 6752 (Colpi, Possenti & Gualandris 2002).

Furthermore, many of the GCs dominated by isolated pulsars appear to have a slower pulsar population (Verbunt 2003), even in surveys where such clusters are observed with uniform sensitivity to fast-spinning pulsars, as in the comparison of M3/M5/M13 with M15 (Hessels et al. 2007) or NGC 6440/6441 with Terzan 5 (Freire et al. 2008a). It is likely that the high stellar densities of some GC cores are also disrupting X-ray binaries, leaving behind partially recycled pulsars.

3.4. Young pulsars in globular clusters

Some pulsars in GCs (PSR B1718−19 in NGC 6342 (Lyne et al. 1993), PSR B1820−30B (Biggs et al. 1994) and J1823−3021C (Lynch et al. 2012) in NGC 6624 and B1745−20 in NGC 6440 (Lyne et al. 1996)) have characteristics very similar to the normal pulsars found in the Galactic disk: periods of the order of a few tenths of a second, magnetic fields of the order of $10^{11} - 12$ G and characteristic ages of a few times $10^7$ yr - about $10^3$ times younger than the stellar population in GCs. Clearly these pulsars cannot have formed in recent iron core collapse SNe — there have not been any since the first few tens of Myr of the histories of these clusters. The partial recycling described above could be spinning up old, dead NSs just enough to make them active radio pulsars, but without going on for long enough to bury their magnetic fields (Lyne et al. 1996).

An alternative hypothesis, also discussed in Lyne et al. (1996) is ongoing formation of new NSs through e-capture SNe. If this hypothesis is correct, then the SNe must have small kicks, otherwise, the formation rates required by the observed population would be unrealistic (Boyles et al. 2011).

4. Exotic pulsars in GCs

4.1. Eccentric binary MSPs & their uses

The first pulsar in an eccentric binary discovered in a GC was PSR B2127+11C (Anderson et al. 1990). This is very similar to the original binary pulsar, B1913+16 (Hulse & Taylor 1975, Weisberg et al. 2010), so it does not indicate anything special is happening in GCs. The discovery of PSR B1802−07, in the GC NGC 6539 (D’Amico et al. 1993) revealed a type of system unknown in the Galactic disk: a relatively fast-spinning pulsar ($P = 23.1$ ms) with a low-mass ($M_c \sim 0.3M_\odot$) companion and an eccentric ($e = 0.21$) orbit. All similar systems then known in the Galaxy had very low ($< 10^{-3}$) eccentricities. This indicated severe orbital perturbations by passing stars (Phinney 1993), something to be expected given the high stellar densities in the cores of GCs.

The discovery of PSR J0514−4002A, in NGC 1851, an MSP with a spin period of 4.99 ms, a very eccentric ($e = 0.888$) 18.8-day orbit (Freire et al. 2004) and massive companion indicates very conclusively that the pulsar exchanged companions after being recycled: the companion is too massive ($M_c > 0.96M_\odot$, Freire, Ransom & Gupta 2007) for its progenitor to have recycled the pulsar to its current spin period. This is also the case for at least another system, PSR J1807−2500B, in NGC 6544 (Lynch et al. 2012). Thus, this sort of system bears witness to the very same process that lead to the recycling of so many pulsars in GCs. Their dense environments can produce binary pulsars (and binary systems in general) that are truly unlike anything that binary stellar evolution can produce in the Galactic disk. These are the systems we designate here as “exotic”.

A total of 19 eccentric ($e > 0.2$) systems have been discovered in GCs (e.g. Ransom et al. 2004, Possenti et al. 2005, Freire et al. 2008a, DeCesar, Ransom & Ray 2011, Lynch et al. 2012), including 7 such systems in Terzan 5 alone (Ransom et al. 2005).
The eccentricities allow at least the measurement of the rate of advance of periastron. When this effect is due to the effects of general relativity alone it yields an estimate of the total mass of the binary (D’Amico et al. 1993, Freire et al. 2003, Ransom et al. 2005, Freire, Ransom & Gupta 2007, Freire et al. 2008a, Freire et al. 2008b). When more Post-Keplerian measurements become available, we can measure individual masses precisely and in some cases test general relativity (Lynch et al. 2012, Jacoby et al. 2006).

4.2. Eclipsing binaries

Until recently, it appeared that one of the distinctive characteristics of the pulsar population in GCs was the large number of eclipsing binaries: 21 known at present. Until 2009, only two were known in the Galactic disk, the original “Black Widow” system, PSR B1957+20 (Fruchter, Stonebring & Taylor) and PSR J2051−0827 (Stappers et al. 1996). Furthermore, several of the eclipsing systems discovered in GCs [e.g., PSR B1718−19 in NGC 6342 (Lyne et al.1993), PSR J1748−2446A, P and ad in Terzan 5 (Lyne et al. 1990, Ransom et al. 2005, Hessels et al. 2006), J0024−7204W in 47 Tuc (Camilo et al. 2000, Edmonds et al. 2002), J1740−5340 in NGC 6397 (D’Amico et al. 2001, D’Amico et al. 2001, Ferraro et al. 2001), J1701−3006B in M62 (Possenti et al. 2003) and PSR J2140−2310A in M30 (Ransom et al. 2004)] had in some cases very extensive eclipses and non-degenerate companions with a few tenths of a solar mass. Because these systems (nicknamed “Redbacks” by Mallory Roberts) had no counterpart in the Galaxy, they were thought to be “exotic”, i.e., results of exchange interactions where a radio pulsar acquires a new main-sequence companion.

However, it was suggested that, due to its similarity with SAX J1808.4−3658 (the first accreting MSP, Wijnands & van der Klis 1998), 47 Tuc W might also represent a transitional object (Bogdanov et al. 2005), not an exotic system. The building of the LMXB-MSP bridge continued with the discovery of PSR J1023+0038 (Archibald et al. (2009)), the first Galactic “Redback”, which showed these objects are not restricted to GCs. The number of eclipsing systems in the Galaxy has since increased dramatically, in great part due to the launch of the Fermi satellite. The tale is told by Mallory Roberts in these proceedings. The “Black Widow” and “Redback” systems are much more abundant in the Galactic disk than previously thought. Despite this, some eclipsing systems in GCs are likely to be truly “exotic”, like PSR B1718−19 (van Kerkwijk et al. 2000).

4.3. Super-energetic MSPs: in GCs and in the Galaxy?

In GCs, there are two MSPs that appear to have unusually high magnetic fields, very large spin-down energies and ages smaller than 30 Myr — about 0.3 % of the age of the clusters that host them. One of them is the first GC pulsar, PSR B1821−24. Soon after its period derivative ( ˙P) was measured (Foster et al. 1988), the unusual nature of the MSP was noticed and discussed. It was deemed to be unlikely that a contribution from the cluster acceleration could be the cause for the anomalous ˙P.

There is firmer evidence of this for the second “super-energetic” MSP to be discovered, PSR B1820−30A in NGC 6624 (Biggs et al. 1994). Initially the discoverers suggested that the very high ˙P was due to acceleration in the cluster; this is a possibility given that the cluster has a collapsed core and the pulsar is (at least in projection) very close to the center. However, the high γ-ray luminosity of this object (Freire et al. 2011) implies that this pulsar has to be energetic and quite young.

These MSPs have lifetimes  10^2 times shorter than the more normal MSPs and are about 10^2 times less abundant; therefore both types must be forming at comparable rates. We list three main possibilities for their formation process: (a) These pulsars were members of now disrupted X-ray binaries, where spin-up went much further than for the
young, slow pulsars, but where the “burial” of the magnetic field was not concluded. This would nicely explain why both objects are single. (b) These pulsars could result from AIC or merger-induced collapse of WDs (Ivanova et al. 2008). (c) They might have an identical formation channel to other MSPs (Tauris, Langer & Kramer 2012). If (a) is correct, then these super-energetic MSPs are “exotic”, i.e., only found in GCs. Otherwise we should see similar systems in the Galaxy, likely associated with gamma-ray sources. As the present generation of high-resolution 20-cm surveys probes deeper into the Galaxy for MSPs (Cordes et al. 2006, Keith et al. 2010, Boyles et al. 2012, Lynch et al. 2012) we might soon know whether pulsars like PSR B1820–30A and B1821–24A exist outside GCs or not. Finding them would have grand implications: it would mean that they are forming at rates similar to normal MSPs through the Universe and that MSPs are born with a range of magnetic fields wider than currently believed; the observation that the majority of MSPs have very low B-fields would then be a selection effect caused by low B-field MSPs being much longer lived.

5. Is there a low-velocity NS population in the Galaxy?

If e-capture SNe are forming NSs in GCs, they should also be forming NSs in the Galaxy: nothing about them is exclusive to GCs. A low-velocity NS population has indeed been suggested several times from proper motion data of radio pulsars (e.g., Arzoumanian, Chernoff & Cordes 2002), but this signature is not clear and could be due instead to projection effects (Hobbs et al. 2005). This might be explained if e-capture SNe result only from AIC of a massive O-Ne-Mg WD (or, alternatively, from the merger of two WDs), i.e., if it requires evolution in a binary system (Podsiadlowski et al. 2004). If this is true, then binary systems are the place to look for evidence of NSs formed in e-capture SNe in the Galaxy.

The binaries seem to agree. Pfahl et al. (2002) identified a class of high-mass, long orbital period (\(P_b > 30\) days) low-eccentricity X-ray binaries (the prime example being X Per/4U 0352+309), in which the NSs must have been born with a low kick velocity. Later, remarking the low eccentricities of several double neutron star systems, van den Heuvel (2004) suggested that the second-born NSs in those systems were produced by e-capture SNe. An additional piece of evidence in these systems is the NS mass measurements, some of them as low as 1.25 M\(_\odot\) (e.g., Kramer et al. 2006), as expected from the gravitational collapse of a contracting O-Ne-Mg core that is just beyond its Chandrasekhar mass (1.38 M\(_\odot\), see Schwab, Podsiadlowski & Rappaport 2010 and references therein).

There is also some evidence for systems where the first formed NS has a very low mass and low velocity, (PSR J1802–2124; Ferdman et al. 2010), or a very small vertical velocity and possibly a small NS mass (PSR J1949+3106; Deneva et al. 2012), however the massive WD progenitors should have diminished post-SN velocities of these binaries. Another case is PSR J1903+0327 (Champion et al. 2008), the first MSP discovered in the ALFA pulsar survey (Cordes et al. 2006). This anomalous pulsar was likely formed in a triple system (Freire et al. 2011, Portegies Zwart et al. 2011), but the preservation of the triple requires a very small kick velocity (Pijloo, Caputo & Portegies Zwart 2012); this is consistent with the very small peculiar velocity of this system (Freire et al. 2011).

Systems where the first NS formed in e-capture SNe should constitute a dynamically separate NS population in the Galaxy with very low scale height; furthermore many of the NSs should have distinctively low masses. Proper motion measurements of the many MSPs being discovered in the current high-resolution 20 cm surveys should be able to determine whether such a population exists and determine its size.
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Pulsar Wind Nebulae: On their growing diversity and association with highly magnetized neutron stars

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Abstract. The 1968 discovery of the Crab and Vela pulsars in their respective supernova remnants (SNRs) confirmed Baade and Zwicky’s 1934 prediction that supernovae form neutron stars. Observations of Pulsar Wind Nebulae (PWNe), particularly with the Chandra X-ray Observatory, have in the past decade opened a new window to focus on the neutron stars’ relativistic winds, study their interaction with their hosting SNRs, and find previously missed pulsars. While the Crab has been thought for decades to represent the prototype of PWNe, we now know of different classes of neutron stars and PWNe whose properties differ from the Crab. In this talk, I review the current status of neutron stars/PWNe-SNR associations, and highlight the growing diversity of PWNe with an X-ray eye on their association with highly magnetized neutron stars. I conclude with an outlook to future high-energy studies.

Keywords. stars: neutron, (stars:) pulsars: general, (ISM:) supernova remnants, X-rays: ISM

1. Brief history and current status of pulsar–PWN–SNR associations

Shortly after the discovery of the neutron particle by Chadwick (1932), Baade and Zwicky (1934) made the seminal prediction that neutron stars are born in supernovae. Very little was known about the manifestation of these objects until Jocelyn Bell and Antony Hewish discovered the first pulsating star with a period of 1.3 sec (Hewish et al. 1968), now known as PSR B1919+21. In the same year, the Crab (Staelin & Reifenstein 1968, Lovelace et al. 1968) and Vela (Large et al. 1968) pulsars were discovered in their respective supernova remnants (SNRs) confirming the 1934 prediction for the association of neutron stars with supernovae.

On the theoretical side, Pacini (1967)‡, Gold (1968), Pacini & Salvati (1973), and Rees & Gunn (1974) introduced the theory that the emission from a neutron star is powered by its rotational energy loss, $E=4\pi^2 I\dot{P}/P^3$ (with $P$ and $\dot{P}$ being the rotation period and its derivative), with the pulsar generating a magnetized particle wind whose ultra-relativistic electrons and positrons emit synchrotron radiation across the electromagnetic spectrum. As this wind encounters its confining surrounding medium, it gets shocked forming a nebula referred to as a pulsar wind nebula (PWN, also known as plerion).

PWNe, being the bubbles inflated by the spin-down energy of the pulsar, have proven to be excellent pathfinders for pulsar discovery. Even in the absence of direct pulsar detection, their emission immediately implies the presence of a neutron star whose properties ($E$, $P$, $\dot{P}$, characteristic age $\tau_c=P/2\dot{P}$, and dipole magnetic field $B=3.2\times10^{19} (P\dot{P})^{1/2} G$) can be directly inferred from the properties of the PWN (see Gaensler & Slane 2006 and Kargaltsev & Pavlov 2008 for reviews).

‡ a pioneer in PSR theory who recently passed away (25 Jan. 2012); a few months before PSR discovery, he predicted that neutron stars could release their rotational energy through jets.
Up to the early 1990s only a handful of neutron stars were known to be associated with SNRs. The number of associations has however significantly increased with the synergy of radio and X-ray studies, particularly with the imaging and spectroscopic capabilities of the *ROSAT* and *ASCA* missions in the 1990s, and since 2000 with the *Chandra* and *XMM-Newton* missions. *ASCA*’s coverage in the hard X-ray band \((E \gtrsim 2\) keV) has been particularly instrumental in identifying PWNe inside SNRs, therefore revealing new pulsars following targeted radio and X-ray pulsation searches. *Chandra*’s superb imaging resolution has opened a new window to image these fascinating objects through revealing high-resolution, arcsecond-scale, structures associated with the deposition of the pulsar’s wind energy into its surroundings, and to pin down their powering engines.

Currently out of the 309 known Galactic SNRs, 103 are associated with a neutron star or a neutron star candidate, with 85 being identified as a pulsar. A PWN is detected or suggested in 87 cases, with 62 SNRs associated with both a PWN and a neutron star or pulsar (see Ferrand & Safi-Harb 2012 and these proceedings).

2. The growing diversity of neutron stars and PWNe

One of the major discoveries advanced in the past decade, thanks to the synergy of radio and X-ray observations, is the growing diversity of neutron stars. These include, in addition to the rotation-powered pulsars (RPP) like the Crab, the Anomalous X-ray pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) dubbed as ‘magnetars’ with surface dipole magnetic fields, \(B\), exceeding the quantum electrodynamic threshold \(B_{\text{QED}} = 4.4 \times 10^{13}\) G, the high-magnetic field radio pulsars (HBPs) with magnetic fields intermediate between the Crab-like pulsars and magnetars, the Rotating Radio Transients (RRATs), and the Central Compact Objects (CCOs) inside SNRs currently believed to be ‘anti-magnetars’ (see Mereghetti 2008, Ng & Kaspi 2011, Keane et al. 2011, and Gotthelf & Halpern 2008, respectively, for reviews on these neutron star classes). Among the 103 neutron star–SNR associations, 10 SNRs are associated with magnetars or magnetar candidates (including 6 proposed associations), 2 SNRs are securely associated with HBPs, 13 SNRs are associated or proposed to be associated with CCOs/CCO candidates, with the remaining SNRs associated with RPPs or candidate neutron stars.

An outstanding question in this field is whether these apparently different classes of neutron stars are linked. It is now clear (e.g. from the discovery of radio emission from a few magnetars, magnetar-like activity of the HBP J1846–0258 in the SNR Kes 75, and the existence of low-B magnetars like SGR 0418+5729) that the dipole magnetic field is not the sole factor determining their observational properties. One big unknown is their environment and progenitors (see Safi-Harb & Kumar, these proceedings). Studies and/or searches for any associated PWNe can help shed light on these questions and provide further clues on the nature of their emission mechanism and their confining environment.

In fact, SNR studies, conducted in parallel with neutron stars studies, have also revealed new classes of PWNe with properties unlike the Crab nebula long thought to be the prototype PWN. These include PWNe expanding into bubbles blown by their progenitors, evolved objects powering X-ray nebulae that are offset from their radio counterparts, or compact X-ray PWNe powered by pulsars with likely highly magnetized winds. Coordinated targeted radio and X-ray studies of such unusual PWNe are revealing pulsar candidates awaiting discovery, or interesting pulsars such as the highly energetic 24 ms pulsar recently discovered in the SNR G76.9+1.0 (Arzoumanian et al. 2011). The diversity arising from such ‘unusual’ and evolved PWNe has been highlighted elsewhere (Safi-Harb 2012). In this paper, I review the growing evidence for PWNe around the highly magnetized neutron stars and the clues they offer about their powering engines.
3. Magnetar Wind Nebulae?

Whether highly magnetized neutron stars (magnetars and HBPs with \( B \geq 4 \times 10^{13} \, \text{G} \)) should power PWNe is an open and interesting question. For PWNe to form, one generally needs a relativistic particle outflow in a strongly magnetized and confining medium. Magnetars have been suggested to produce steady or post-outburst particle outflows (e.g., Harding et al. 1999). Evidence for an intermittent outflow came with the discovery of a radio nebula around SGR 1806–20 following its 2004 December 27 giant flare (Gaensler et al. 2005). It’s not clear however whether steady magnetar outflows can power detectable PWNe. Their presence is of particular interest since they reflect the energy budget released over the pulsar’s lifetime. In addition, their X-ray spectral properties shed light on whether they are rotation- or magnetically-powered, thus providing further clues to their possible link to the classical RPPs.

One of the challenges in identifying PWNe around magnetars lies in the magnetars’ relatively high X-ray luminosity combined with heavy interstellar absorption causing the formation of a dust scattering halo around them. Furthermore, typically the X-ray luminosity of the PWNe associated with the RPPs is only a small fraction of their spin-down energy (\( L_x \sim 10^{-5} - 10^{-2} \dot{E} \)). For magnetars, the spin-down energy is very small, ranging from \( \sim 3 \times 10^{39} \, \text{erg s}^{-1} \) for SGR 0418+5729 to \( \sim 2 \times 10^{35} \, \text{erg s}^{-1} \) for 1E 1547.0–5408, with typical values of \( \sim 10^{33} \, \text{erg s}^{-1} \). Therefore, assuming a similarly small X-ray to spin-down luminosity ratio for steady PWNe around magnetars, very deep high-resolution X-ray observations will be needed to identify any associated PWN. Furthermore, the highest \( \dot{E} \) magnetars would be the more promising candidates for PWN searches.

So far, X-ray PWNe have been detected around the high-magnetic field pulsars J1119–6127, J1846–0258, and RRAT J1819–1458 (the highest \( B \) source among the RRATs) using *Chandra*, and the SGR Swift J1834.9–0846 using *XMM-Newton*; see Table 1 for a summary of their properties, together with Figures 1 and 2 for their locations on the

![Figure 1. P–\( \dot{P} \) diagram for the rotation-powered pulsars (RPPs) and highly magnetized neutron stars (HBPs, AXPs and SGRs), highlighting the X-ray PWNe detected (green circles) or claimed (dashed green circle) around highly magnetized neutron stars with \( B \geq 4 \times 10^{13} \, \text{G} \).](image)
Figure 2. X-ray PWNe around highly magnetized neutron stars: (a) the SGR Swift J1834.9–0846 with XMM-Newton showing the extended emission post- (top) and pre- (bottom) outburst observed in 2011, (b) the HBP J1119–6127 in SNR G292.2–0.5 with Chandra showing a compact PWN and a jet, (c) the youngest HBP J1846–0258 in SNR Kes 75 with Chandra revealing high-resolution structures and variability associated with the magnetar-like outburst observed in 2006, and (d) the highest-B RRAT J1819–1458 showing a compact PWN with Chandra (see also Camero et al., these proceedings). Figure adapted from figures published in Younes et al. 2012, Safi-Harb & Kumar 2008, Ng et al. 2008, and Rea et al. 2009.

As shown in Table 1, these nebulae are compact and display a wide range of spectral indices and X-ray luminosities (or ratios with respect to their pulsar’s spin-down luminosity). The compact PWN surrounding PSR J1119–6127 is characterized by a hard power-law photon index (noting the jet’s photon index is also hard, $\Gamma = 1.4^{+0.2}_{-0.7}$) and a low X-ray to spin-down luminosity ratio, very similar to the properties of PWNe associated with RPPs (Safi-Harb & Kumar 2008). To date, this pulsar hasn’t shown evidence for a magnetar-like burst. PSR J1846–0258, an HBP with spin properties similar to PSR J1119–6127 (although younger and not yet detected as a radio pulsar), has shown evidence for magnetar-like behaviour and variability in the PWN properties (Gavriil et al. 2008, Kumar & Safi-Harb 2008, Ng et al. 2008). This so far remains the only HBP that has shown ‘schizophrenic’ behaviour (i.e. RPP and magnetar-like) suggesting that HBPs can be powered by both rotational energy and magnetic field decay (Camilo 2008). PSR J1119–6127 and PSR J1846–0258 are the only HBPs known to date to be securely associated with SNRs (as expected from their youth). They are both characterized by a high $\dot{E}$ and have a measured braking index yielding a more accurate estimate for their
actual ages. For PSR J1119–6127, the recently refined braking index measurement using more than 12 years of radio timing data of $n = 2.684 \pm 0.002$ (Weltevrede et al. 2011) implies an upper limit on its age of 1.9 kyr, smaller than the estimated age of 4.2–7.1 kyr for its associated SNR, G292.2–0.5 (Kumar et al. 2012). This apparent age discrepancy can be attributed to a variable braking index for the pulsar, which has recently also shown some unusual timing characteristics at radio wavelengths.

The photon index for the PWNe associated with both above-mentioned HBPs is relatively hard and consistent with that observed in the RPPs’ PWNe. For the RRAT and the Swift sources however, their PWNe have a much steeper photon index, more similar to that observed in the (soft) power-law component of AXPs in the 0.5–10 keV band, suggesting a similar population of particles emitting in X-rays. The X-ray to spin-down luminosity of the three secure PWNe (excluding 1E 1547.0–5408 and with the exception of PSR J1119–6127) is relatively large in comparison to the RPPs. That, together with their relatively steep photon index and evidence of variability, suggests that their X-ray luminosity is not entirely powered by rotation, but possibly by some additional source of magnetic energy. Energetically however, they can still be powered by rotation given that their X-ray luminosity is still smaller than their spin-down luminosity.

4. Conclusions and future prospects

The pulsar/SNR community has gone a long way since the discovery of the neutron and the prediction of neutron star-SNR association some 80 years ago, followed by the discovery of pulsars 44 years ago. The nebulae blown by their relativistic winds offer a unique astrophysical laboratory for pulsar discovery and for probing their outflows, environment, and diversity. The recent discoveries of PWNe around high-B pulsars are opening a new window to address their link to the more classical RPPs.

Many questions remain to be answered. In particular we don’t know whether (all) high-B neutron stars should power steady PWNe, and if so what powers their X-ray emission and what specifically distinguishes them from (or links them to) the other neutron star classes. Monitoring these sources, together with targeted deep X-ray and γ-ray observations, will help settle the puzzle about the driving mechanism and energy budget for their high-energy emission. As well, the question on the (still) missing pulsars in many SNRs can be addressed with coordinated radio and high-energy studies and pulsation searches, especially in the X-ray detected PWNe.

We hope for many more years for the currently operating X-ray missions, in particular

| Table 1. X-ray PWNe around high-B pulsars listed in the order of increasing $B$. |
|---------------------------------|----------|--------|--------|--------|--------|--------|--------|
| PSR               | $P$ (s)  | $B$ (10$^{13}$G) | $E$ (erg s$^{-1}$) | $\tau_c$ | $\gamma$ | $L_x$ (erg s$^{-1}$) | SNR? |
| J1119–6127        | 0.408   | 4.1    | 2.3×10$^{36}$ | 1.7 | 6×15$^\prime$ | 1.1$^{+0.9}_{-0.7}$ | 5×10$^{-4}$ | G292.2–0.5 | [1] |
| J1846–0258        | 0.324   | 5      | 8.3×10$^{36}$ | 0.7 | 40$^\prime$ | 1.8$^{+0.1}_{-0.2}$ | 0.3–0.3 | Kes 75 | [2] |
| J1819–1458        | 4.26    | 5      | 3×10$^{32}$ | 117 | $\sim 13^\prime$ | 3.0$^{+1.5}_{-0.2}$ | 0.2–0.7 | 3 |
| J1834.9–0846      | 2.48    | 14     | 2.1×10$^{34}$ | 5 | 70–150$^\prime$ | 3.5$^{+0.6}_{-0.7}$ | 0.7 | W41? | [4] |
| 1E 1547.0–5408    | 2.07    | 32     | 1.0×10$^{35}$ | 0.7 | 45$^\prime$ | 3.4$^{+0.4}_{-0.1}$ | 0.01 | G327.2–0.1 | [5] |

Chandra as it has been instrumental in detecting PWNe and localizing previously missed pulsars. The hard X-ray (5–80 keV) capabilities of NuSTAR, successfully launched in June 2012, the broadband coverage (0.3-600 keV) of ASTRO-H slated for launch in 2014, and the MeV to TeV coverage with existing and upcoming gamma-ray facilities, will provide a new window to the high-energy studies of these fascinating objects.

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References
Constraining the luminosity function parameters and population size of radio pulsars in globular clusters

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Abstract. The luminosity distribution of Galactic radio pulsars is believed to be log-normal in form. Applying this functional form to populations of pulsars in globular clusters, we employ Bayesian methods to explore constraints on the mean and standard deviation of the function, as well as the total number of pulsars in the cluster. Our analysis is based on an observed number of pulsars down to some limiting flux density, measurements of flux densities of individual pulsars, as well as diffuse emission from the direction of the cluster. We apply our analysis to Terzan 5 and demonstrate, under reasonable assumptions, that the number of potentially observable pulsars is in a 95.45% credible interval of $133^{+101}_{-58}$. Beaming considerations would increase the true population size by approximately a factor of two.

Keywords. methods: numerical — methods: statistical — globular clusters: general — globular clusters: individual: Terzan 5 — stars: neutron — pulsars: general

1. Introduction

Globular clusters have high core stellar number densities that favour the formation of low-mass X-ray binaries (LMXBs) that are believed to be the progenitors of millisecond pulsars (MSPs; Alpar et al. 1982). MSPs can be considered long-lived tracers of LMXBs, so constraints on the MSP content provide unique insights into binary evolution and the integrated dynamical history of globular clusters, while determining the radio luminosity function of these pulsars helps shed light on their emission mechanism.

Faucher-Giguère & Kaspi (2006) have shown that the luminosity distribution of non-recycled Galactic pulsars appears to be log-normal in form. More recently, Bagchi et al. (2011) have verified that the observed luminosities of recycled pulsars in globular clusters are consistent with this result. Assuming, therefore, that there is no significant difference between the nature of Galactic and cluster populations, we use Bayesian techniques to investigate some of the consequences that occur when one applies this functional form to populations of pulsars in individual clusters. We are interested in the situation where we observe $n$ pulsars with luminosities above some limiting luminosity. There is a family of luminosity function parameters ($\mu, \sigma$) and population sizes ($N$) that is consistent with this observation, and here we analyze the posterior probabilities of different members of this family given the data. In our case, the data are the individual pulsar flux densities.
that we call \( \{S_i\} \), the observed number of pulsars, \( n \) and the total diffuse flux density of the cluster, \( S_{\text{obs}} \).

### 2. Bayesian parameter estimation

Luminosity and flux density are related by the standard pseudo-luminosity equation \( L = S r^2 \), where \( r \) is the distance to the pulsar (see Lorimer & Kramer 2005). This implies that the luminosity function is corrupted by uncertainties in distance. To mitigate this, we decided to perform our analysis initially in terms of the measured flux densities, and use a model of distance uncertainty to convert our results to the luminosity domain. We take the distance to all pulsars in a cluster to be the same. The log-normal in luminosity can then alternatively be written in terms of flux density. The probability of detecting a pulsar with flux density \( S \) in the range \( \log S \) to \( \log S + d(\log S) \) is given by a log-normal in \( S \) as

\[
p(\log S) d(\log S) = \frac{1}{\sigma_S \sqrt{2\pi}} e^{-\frac{(\log S - \mu_S)^2}{2\sigma_S^2}} d(\log S),
\]

where \( S \) is in mJy, and \( \mu_S \) and \( \sigma_S \) are the mean and standard deviation of the flux density distribution. The probability of observing a pulsar above the limit \( S_{\text{min}} \) is then

\[
p_{\text{obs}} = \int_{\log S_{\text{min}}}^{\infty} p(\log S) d(\log S) = \frac{1}{2} \text{erfc} \left( \frac{\log S_{\text{min}} - \mu_S}{\sqrt{2} \sigma_S} \right).
\]

First, we consider as data the measured flux densities of pulsars in the cluster, \( \{S_i\} \).

Ideally, the survey sensitivity limit \( S_{\text{min}} \) can be taken as another datum, but its exact value is not always known, so we decided to parametrize \( S_{\text{min}} \). The likelihood of observing a set of pulsars with fluxes \( \{S_i\} \) is represented as

\[
\Pi_{i=1}^{n} p_i(\log S_i|\mu_S, \sigma_S, S_{\text{min}}) = \Pi_{i=1}^{n} \frac{1}{p_{\text{obs}} \sigma_S \sqrt{2\pi}} e^{-\frac{(\log S_i - \mu_S)^2}{2\sigma_S^2}}
\]

where \( n \) is the number of observed pulsars in the cluster, and \( p_{\text{obs}} \) is as given in Equation (2.2). Uncertainties in the flux density measurements are not considered here, but it has to be noted that it will have the effect of underestimating the credible intervals on our posteriors.

To infer the total number of pulsars in the cluster, we follow Boyles et al. (2011) to take as likelihood the probability of observing \( n \) pulsars in a cluster with \( N \) pulsars, given by the binomial distribution

\[
p(n|N, \mu_S, \sigma_S, S_{\text{min}}) = \frac{N!}{n!(N-n)!} p_{\text{obs}}^n (1-p_{\text{obs}})^{N-n}.
\]

Next, we incorporate information about the observed diffuse flux from the direction of the cluster. We assume that all radio emission is due to the pulsars in the cluster, both resolved and unresolved. For the likelihood of measuring the diffuse flux \( S_{\text{obs}} \), we choose

\[
p(S_{\text{obs}}|N, \mu_S, \sigma_S) = \frac{1}{\sigma_{\text{diff}} \sqrt{2\pi}} e^{-\frac{(S_{\text{obs}} - \mu_{\text{diff}})^2}{2\sigma_{\text{diff}}^2}},
\]

where \( S_{\text{diff}} \) is the expectation of the total diffuse flux of a cluster whose flux density distribution is a log-normal with parameters \( \mu_S \) and \( \sigma_S \), and having \( N \) pulsars, and \( \sigma_{\text{diff}} \) is the standard deviation. Here, \( \mu_{\text{diff}} = N \langle S \rangle \) and \( \sigma_{\text{diff}} = \sqrt{N} \text{SD}(S) \) where the expectation of \( S \) is given by \( \langle S \rangle = 10^{\mu_S + \frac{1}{2} \sigma_S^2 \ln(10)} \) and the standard deviation of \( S \), \( \text{SD}(S) = 10^{\mu_S + \frac{1}{2} \sigma_S^2 \ln(10)} \sqrt{10\sigma_S^2 \ln(10)} - 1 \).
diffuse flux measurement. The total likelihood, \( p(\log S_i, n, S_{\text{obs}}|N, \mu_S, \sigma_S, S_{\text{min}}) \) is the product of the three likelihoods computed above.

The flux density distribution of pulsars in a cluster is not suitable for comparing the populations in different clusters, as it depends on the distance to the cluster. So we transform the total likelihood obtained in the previous subsection to the luminosity domain. Taking into account the uncertainty in distance as a distribution of distances, \( p(r) \), it can be shown that the total likelihood in the luminosity domain is

\[
p(\log S_i, n, S_{\text{obs}}|N, \mu, \sigma, S_{\text{min}}, r) = p(\log S_i, n, S_{\text{obs}}|N, \mu_S, \sigma_S, S_{\text{min}}).
\]

(2.6)

where \( \mu \) and \( \mu_S \) are related additively by the term \( 2 \log r \), and \( \sigma \) and \( \sigma_S \) are equal. The final joint posterior in luminosity is then given by

\[
p(N, \mu, \sigma, S_{\text{min}}, r | \log S_i, n, S_{\text{obs}}) \propto p(\log S_i, n, S_{\text{obs}}|N, \mu, \sigma, S_{\text{min}}, r) p(N) p(\mu) p(\sigma) p(S_{\text{min}}) p(r).
\]

(2.7)

The prior on \( N \) is taken to be uniform from \( n \) to \( \infty \). We also use uniform priors on the model parameters \( \mu \) and \( \sigma \). We choose a uniform prior on \( S_{\text{min}} \) in the range \( (0, \min(S_i)) \], where the upper limit is the flux density of the least bright pulsar in the cluster. The prior on \( r \) is taken to be a Gaussian. This joint posterior is integrated over various sets of model parameters to obtain marginalized posteriors.

3. Applications

We applied our Bayesian technique to Terzan 5. Although Terzan 5 has 34 known pulsars (Ransom S. M., private communication), we take \( n = 25 \), the number of pulsars for which we have flux density measurements. The flux densities of the individual pulsars were collected in a literature survey (Bagchi et al. 2011 and references therein). The flux densities we used were scaled from those reported at 1950 MHz by Ransom et al. (2005) and Hessels et al. (2006) to 1400 MHz using a spectral index, \( \alpha = -1.9 \), using the power law \( S(\nu) \propto \nu^\alpha \). The observed diffuse flux density at 1400 MHz is taken to be \( S_{\text{obs}} = 5.2 \) mJy (Fruchter & Goss 2000). The prior on \( N \) was chosen to be uniform in \([n, 500]\), which is sufficiently wide to ensure that the posterior does not rail against the prior boundaries. We chose uniform distributions in the same range of \( \mu \) and \( \sigma \) as used by Bagchi et al. (2011) as our priors. We took \( S_{\text{min}} \) to be uniform in \((0, \min(S_i))\]. The most recent measurement of the distance to Terzan 5, \( r = 5.5 \pm 0.9 \) kpc (Ortolani et al. 2007), was used to model the distance prior as a Gaussian. Figure 1 shows the results of the analysis. The median values of the three parameters with 95.45\% credible intervals are: \( N = 92^{+318}_{-64} \), \( \mu = -0.9^{+1.2}_{-1.1} \) and \( \sigma = 0.9^{+0.3}_{-0.4} \).

Note that \( N \) is the size of the population of pulsars that are beaming towards the Earth. Uncertainties notwithstanding, the beaming fraction of MSPs is generally thought to be > 50\% (Kramer et al. 1998). This, together with the fact that most pulsars in globular clusters are MSPs, imply that the true population size in a cluster is approximately a factor of two more than the potentially observable population size.

3.1. Using prior information

In the framework developed in the previous section, we use broad uniform (non-informative) priors for the mean and standard deviation of the log-normal. This lack of prior information is apparent in Figure 1(b), where \( N \) is not very well constrained. Prior information can help better constrain the parameters of interest. Boyles et al. (2011) use models of Galactic pulsars from Ridley & Lorimer (2010) to narrow down \( \mu \) to between \(-1.19 \) and \(-1.04 \), and \( \sigma \) to the range \( 0.91 \) to \( 0.98 \). We have chosen our priors on \( \mu \) and \( \sigma \)
Figure 1. Results of the analysis for Terzan 5. For (a) and (b), the analysis was run with wide priors on $\mu$ and $\sigma$, with the ranges equal to those used by Bagchi et al. (2011), their Figure 2. (a) depicts the joint posterior on $\mu$ and $\sigma$, marginalized over $N$, $S_{\text{min}}$, and $r$; (b) is the marginalized posterior for $N$. (c) Posterior on $N$ after applying narrow priors on $\mu$ and $\sigma$. In (b) and (c), the shaded regions lie outside a 95.45% credible interval.

...to be uniform within these ranges. Applying the Bayesian analysis over this narrower range of $\mu$ and $\sigma$ results in much tighter constraints on $N$ as seen in Figure 1(c), where $N = 133^{+101}_{-58}$. This result is consistent with that of Bagchi et al. (2011).

4. Conclusions

The technique described here would be useful in future studies of the globular cluster luminosity function where ongoing and future pulsar surveys are expected to provide a substantial increase in the number of known pulsars in many clusters. We anticipate that the increased amount of data would enable us to constrain the distributions of $\mu$ and $\sigma$ independently (i.e. without the need to assume prior information from the Galactic pulsar population). Further interferometric measurements of the diffuse radio flux in many clusters could provide improved constraints on $\mu$ and $\sigma$ by measuring the flux contribution from the individually unresolvable population of pulsars.

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The extended X–ray emission around RRAT J1819–1458

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Abstract. We present new imaging and spectral analysis of the recently discovered extended X–ray emission around the high-magnetic-field rotating radio transient RRAT J1819–1458. We used two Chandra observations, taken on 2008 May 31 and 2011 May 28. The diffuse X–ray emission was detected with a significance of $\sim$19$\sigma$ in the image obtained by combining the two observations. Long-term spectral variability has not been observed. Possible scenarios for the origin of this diffuse X–ray emission, further detailed in Camero–Arranz et al. (2012), are here discussed.

Keywords. pulsars: individual (RRAT J1819–1458) — stars: magnetic fields — stars: neutron — X–rays: stars

1. Introduction
Rotating Radio Transients (RRATs) are radio pulsars that were discovered through their sporadic radio bursts (McLaughlin et al. 2006). At a radio frequency of 1.4 GHz, radio bursts are observed from RRAT J1819–1458 roughly every $\sim$3 minutes with the Parkes telescope. The spin period of RRAT J1819–1458 is 4.3 s, with a characteristic age of 117 kyr at the 3.6 kpc distance and a dipolar magnetic field of B$\sim$5$\times$10$^{13}$ G. The spin-down energy loss rate measured for this source is $\dot{E}_{\text{rot}}$ $\sim$3$\times$10$^{32}$ erg s$^{-1}$, being the only source of this type also detected in X–rays (Reynolds et al. 2006, McLaughlin et al. 2007, Rea et al. 2008, Kaplan et al. 2009). In this work, we present the study of the extended X–ray emission discovered by Rea et al. (2009), resulting from the reduction and combined analysis of two Chandra observations for RRAT J1819–1458, performed on 2008 and 2011 May 28.
2. Observations and data reduction

The Chandra X-ray Observatory observed RRAT J1819–1458 with the Advanced CCD Imaging Spectrometer (ACIS) instrument on 2008 May 31 (ObsID 7645) for 30 ks and again in 2011 May 28 (ObsID 12670) for 90 ks, both in VERY FAINT (VF) timed exposure imaging mode. For both observations, we used a 1/8 subarray, which provides a time resolution of 0.4 s. Standard processing of the data using CIAO software (ver. 4.4) has been performed.

3. Analysis and results

3.1. Imaging

To study the extended X-ray emission found by Rea et al. (2009) in more detail, we proceeded with the extraction of a combined image in the 0.3–10 keV energy range, using the two Chandra observations using the CIAO tool reproject_image. Figure 1 shows the resultant combined image where diffuse extended X-ray emission is clearly visible around the compact object. We applied the CIAO wavdetect tool to the ∼90 ks ACIS-S cleaned image and found RRAT J1819–1458 at the following position: α = 18h19m34.18s and δ = −14°58′03.7″ (error circle of 0″.5 radius), in agreement with previous results.

3.2. Spectroscopy

We used the CIAO specextract script to extract source and background spectra for RRAT J1819–1458. To increase the signal to noise of the spectrum we proceeded to combine the spectra created for ObsIds 7645 and 12670 using the CIAO tool combine_spectra.
Figure 2. Red circles denote the combined ACIS-S spectrum of RRAT J1819–1458. Blue open triangles represent the combined spectrum of the extended X–ray emission (Camero–Arranz et al. 2012).

(see Figure 2). The combined spectrum was modeled with an absorbed blackbody plus an absorption line at 1 keV. The Hydrogen absorption column was fixed to $0.6 \times 10^{22}$ cm$^{-2}$, allowing us to better constrain the 1 keV line feature. The blackbody temperature obtained was $T_{\text{BBbody}} = 0.130 \pm 0.002$ keV, with $E_{\text{gauss}} = 1.16 \pm 0.03$ keV and $\sigma = 0.17 \pm 0.03$ keV ($\chi^2_r = 1.10$; 44 dof). Figure 2 also shows the $\sim$0.8–7 keV combined spectrum for the extended source. An absorbed power law provides a good fit to the data. The spectral parameters resulted from the best fitting are $\alpha = 3.7 \pm 0.3$ ($\chi^2_r = 1.26$; 19 dof).

3.3. The diffuse X–ray emission structure

To infer the significance and estimate the luminosity of the whole diffuse emission in the combined image, we built the combined Chart/MARX point-spread function (PSF), using both the RRAT J1819–1458 spectrum and its corresponding exposure time. In Figure 3, we compare the surface brightness radial distribution of the combined Chandra observation of RRAT J1819–1458 with that of the combined Chart/MARX PSF plus a background level. This figure shows that the extended emission becomes detectable around 5 pixels ($\sim$2.5") from the peak of the source PSF. To compute the significance of the diffuse X–ray emission around RRAT J1819–1458, from the combined image we extracted all the photons from an annular region of 2".5–20" radii, and we subtracted from it the background extracted from a similar region far from the source. This resulted in an excess of $790 \pm 18$ counts (a detection significance of $\sim$19$\sigma$).
4. Discussion

The energies of pulsar wind electrons and positrons range from \( \sim 1 \) GeV to \( \sim 1 \) PeV, placing their synchrotron and inverse Compton emission into radio–X–ray and GeV–TeV bands, respectively. This multiwavelength emission can be seen as a pulsar-wind nebula. To date, the exact physical origin and acceleration mechanism of the high-energy particles in the pulsar winds are poorly understood, and not all nebulae can be easily explained as spin-down-powered PWNe. In Rea et al. (2009) we discussed different scenarios for the origin of the extended emission detected around RRAT J1819–1458. One option was that the extended emission we observe is part of the remnant of the supernova explosion which formed RRAT J1819–1458, unlikely for an object of 117 kyr. A bow-shock nebula due to the pulsar moving supersonically through the ambient medium was also ruled out due to the projected velocity in the case of a bow shock \( (v_p \sim 20 \text{ km s}^{-1}; \text{see Rea et al. } 2009 \text{ and references therein}) \) being rather small. We propose that RRAT J1819–1458 could power a sort of PWN or the extended X–ray emission around the pulsar might be explained as a magnetic nebula, or as a scattering halo as for 1E 1547–5408 (Vink & Bamba 2009, Olausen et al. 2011) and Swift J1834.9-0846 (Younes et al. 2012; Esposito et al. 2012).

References
Diffusion and advection model for particle transport in young pulsar wind nebulae

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Abstract. The magnetohydrodynamic (MHD) model for young pulsar wind nebulae (PWN) has been successful in reproducing many features of the nebulae. The model is characterized by a termination shock (TS) between the PWN and unshocked pulsar wind. Relativistic particles are injected at the TS and follow an advective flow to the outer boundary. However, toroidal structure of well studied young PWN like the Crab Nebula, 3C 58 and G21.5-0.9 is only present in the region close to the TS. In the outer parts of the nebulae, filamentary and loop-like structure is observed. Also, the radial variation of spectral index due to synchrotron losses is smoother than expected in the MHD flow model. We find that a pure diffusion model with energy independent diffusion and a transmitting boundary can reproduce the basic data on nebular size and spectral index variation for the Crab, 3C 58, and G21.50.9. Energy dependent diffusion is also discussed. Power law variations of the coefficient with energy are degenerate with variation in the input particle energy distribution index in the steady state case. Monte Carlo simulations of particle transport with both diffusion and advection for the Crab nebula and 3C 58 suggest a picture in which advection dominates the inner part of the PWN where toroidal structure is clearly present. Diffusion dominates the outer part of the PWN where filamentary and loop-like structure is observed. The source of the chaotic field is uncertain, but may be related to Rayleigh-Taylor instability at the outer boundary of young nebulae and/or the kink instability of the toroidal magnetic field.

Keywords. ISM: individual (Crab Nebula) — ISM: supernova remnants — pulsars: general — stars: winds, outflows

1. Introduction

Pulsar wind nebulae (PWN), the result of interaction between relativistic pulsar winds and supernova (SN) ejecta, are excellent sites for studying not only pulsar wind dynamics and shock processes but also particle transport and magnetic field evolution (Gaensler & Slane 2006). The current standard picture for particle transport in young PWN is based on the magnetohydrodynamic (MHD) model first presented by Rees & Gunn (1974) and then discussed in detail by Kennel & Coroniti (1984a,b). In the MHD model, particles are accelerated at the termination shock and then follow the downstream advective flow toward the outer boundary. During this process, particles lose energy to synchrotron radiation and adiabatic expansion. The 1-dimensional MHD model by Kennel & Coroniti (1984a,b) successfully explains the diminishing size of the Crab Nebula as the frequency increases and its integrated spectrum from infrared to X-ray wavelengths. The model also predicts a position of the termination shock that is consistent with X-ray observations (Kargaltsev & Pavlov 2008). However, the jet torus structure observed in X-rays cannot be addressed in a 1D model, so attention has turned to 2D and even 3D MHD simulations of young PWN. In 2D simulations, the pulsar power is assumed to depend on pulsar angle; the simulations can reproduce the toroidal structure surrounding the central pulsar...
(Komissarov & Lyubarsky 2003; Del Zanna et al. 2004) and time variability of the inner structure (Volpi et al. 2008; Camus et al. 2009; Komissarov & Lyutikov 2011). The MHD model is successful in explaining many aspects of Crab Nebula and other young PWN, but recent observation of 3C 58 and G21.5-0.9 (Slane et al. 2000, 2008; Safi-Harb et al. 2001) show some features contradicting the MHD model. Both show toroidal structure very close to the central pulsar, but the radial variation of spectral index is smoother than expected in the standard picture. In Tang & Chevalier (2012), we found that adding diffusion to the current picture of particle transport can explain many of these aspects. We propose that both advection and diffusion are important for particle transport in young PWN. Advection dominates particle transport in the region close to the central pulsar, while diffusion dominates the outer part of the PWN.

2. Theoretical model

Our work in Tang & Chevalier (2012) is motivated by the Chandra observations of 3C 58 and G21.5-0.9 (Slane et al. 2000, 2008; Safi-Harb et al. 2001). The radial variation of spectral index is inconsistent with the MHD model but consistent with the profile from a diffusion model (Wilson 1972). We start with a pure diffusion model by Gratton (1972) for particle transport in young PWN with spherical symmetry, transmitting boundary and energy independent diffusion coefficient. We also assume that the magnetic field is constant within the PWN and synchrotron losses are the only energy loss. We use Gratton’s model to fit the spectral index distribution of not only 3C 58 and G21.5-0.9 in X-rays but also the Crab Nebula from radio to optical. We obtained a reduced $\chi^2$ about 0.8 for 3C 58 and 3.3 for G21.5-0.9.

In Gratton’s model, the nebular size of a PWN is determined by a critical frequency $\nu R \propto D^2/R^4 B^3$ where $D$ is the diffusion coefficient, $R$ is the radius of nebular outer boundary and $B$ is the magnetic field. When $\nu < \nu_R$, the nebular size remains the same due to the outer boundary condition. When $\nu > \nu_R$, the size tends to shrink as the cooling time of particles is smaller than the diffusion time. $B$ and $R$ are determined from observation and the diffusion coefficient $D$ can be obtained through model fitting. In our best fit models, $\nu_R = 2 \times 10^{13}$ Hz for the Crab Nebula, $\nu_R = 1.3 \times 10^{18}$ Hz for 3C 58, and $\nu_R = 2.6 \times 10^{17}$ Hz for G21.5-0.9. For the Crab Nebula, X-ray, optical and near-IR frequencies are all in the $\nu > \nu_R$ regime, so the nebular size of the Crab decreases from radio to X-rays. For 3C 58 and G21.5-0.9, all frequencies below soft X-rays are in the $\nu < \nu_R$ regime, so the radio, optical and soft X-ray nebular sizes of 3C 58 and G21.5-0.9 tend to be similar.

We then calculated the size of the Crab Nebula as a function of frequency. The calculated nebular size is smaller than observed at high frequency. A possible reason is that Gratton's model doesn’t take possible energy dependent diffusion into account. Our best fit diffusion coefficient for 3C 58 and G21.5-0.9 in X-rays is larger than the best fit coefficient of the Crab Nebula at optical wavelengths by at least one order of magnitude. If there is energy dependent diffusion, it could help explain the discrepancy in diffusion coefficient among them. Another reason is that in the high frequency band the nebular size is smaller, so advection is more important. Observations show that the toroidal structure is in the region close to central pulsar while filamentary structure dominates the outer part of nebula. We end up with a picture in which advection dominates particle transport in the region close to central pulsar while diffusion dominates the outer part of the PWN. In considering an energy dependent pure diffusion model, we found that power law variations of the diffusion coefficient with energy are degenerate with variation in the input particle energy distribution index in the steady state, transmitting boundary case.
Finally we carried out Monte Carlo simulations for both the Crab Nebula and 3C 58 with diffusion plus advection. In the Monte Carlo simulations, we took the finite size of the termination shock into account and tested the effect of different outer boundary conditions. The diffusion and advection model with a reflecting outer boundary gave the best fit for the spectral index distribution. Adding advection also helped fitting the nebular size behavior for the Crab Nebula.

In Tang & Chevalier (2012), we mainly focused on fitting the spectral index distribution with different models, and gave only a brief discussion of the nebular size behavior of the Crab. Here we specifically consider the nebular size behavior of 3C 58. Based on Gratton’s model, $\nu R = 1.3 \times 10^{18}$ for 3C 58, which indicates that nebular size of 3C 58 shrinks in hard X-rays. This effect may be detectable with the recently launched hard X-ray space telescope NuSTAR. Since 3C 58 has a smaller magnetic field and larger diffusion coefficient than the Crab Nebula, advection should be less prominent in 3C 58 and pure diffusion may be a good approximation. We carried out calculations for the nebular size of 3C 58 as a function of photon energy based on a pure diffusion model (Figure 1). In the calculation we assume 3C 58 is associated with SN 1181. Our simulation results do not fit the observations well. The Chandra data show that the nebular size of 3C 58 does not shrink significantly around a few keV. We also carried out Monte Carlo simulations for 3C 58 with the best fit parameters from Tang & Chevalier (2012). The results are shown in Table 1. Monte Carlo simulation results are more consistent with the Chandra observations and can be used for future comparison with observations. Energy dependent diffusion, which will result in slower shrinking of nebular size as function of photon energy, is not included in the Monte Carlo simulation.

\[ D = 6.1 \times 10^{27} \text{ cm}^2/\text{s} \]

\[ \nu R = 1.3 \times 10^{18} \]

\[ B = 80 \mu \text{G} \]

\[ p = 2.93 \]

**Figure 1.** 3C 58 half-light radius based on a pure diffusion model with $B = 80 \mu \text{G}$ and $p = 2.93$ as in Tang & Chevalier (2012).
Table 1. Half light radius of 3C 58 based on diffusion and advection model

<table>
<thead>
<tr>
<th>photon energy (keV)</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>half light radius (arcsec)</td>
<td>55</td>
<td>48</td>
<td>43</td>
<td>31</td>
</tr>
</tbody>
</table>

3. Discussion

Both diffusion and advection play an important role in particle transport in young PWN. Advection dominates the region close to central pulsar where toroidal structure is clearly observed. Diffusion dominates the outer part of PWN where filamentary structures are detected. A pure diffusion model tends to give a good fit for spectral index distribution and nebular size of young PWN when cooling is not important. When particles suffer strong synchrotron cooling and nebula size begin to shrink quickly, advection plays a greater role as the emission is dominated by the central region. The source of the chaotic field is uncertain, but may be related to the Rayleigh-Taylor instability at the outer boundary and/or the kink instability of the toroidal magnetic field.

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Science with radio pulsar astrometry

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Abstract. High precision astrometry on radio pulsars can provide model-independent estimates of their distances and velocities. Such estimates serve to calibrate models of the Galactic electron density distribution, thereby improving distance estimates for the entire pulsar population. They can provide independent astrometric information for precision pulse timing, reducing the number of fit parameters and thus potentially improving the sensitivity of pulsar timing arrays to the gravitational wave background. Individual neutron stars also serve as laboratories for astrophysics. For example, distances to highly luminous recycled pulsars identified by the Fermi gamma ray space telescope will constrain their energetics and may serve to probe the equation of state for nuclear matter at extremes of density and pressure. Here we provide an update on ongoing astrometry programs with the Very Long Baseline Array and the scientific results from these efforts.
Session 11

Pulsar magnetosphere and emission mechanisms
The complex charm of the pulsar magnetosphere

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Abstract. I give a brief overview of recent results from self-consistent modeling of electron-positrons cascades in pulsar polar caps. These results strongly suggest that the pulsar magnetosphere is a more complex system than was assumed before.

Keywords. stars: neutron, pulsars: general, acceleration of particles, plasmas, radiation mechanisms: nonthermal, magnetic fields

1. Introduction

Radio pulsars are rotationally powered highly magnetized isolated neutrons stars (NS) which emission is produced in their magnetospheres. There are strong observational evidences that pulsar magnetospheres are filled with dense plasma – pulsar wind nebulae (PWNe) are fed by dense flow of relativistic plasma produced by their parent pulsars. Most of theoretical models of pulsar magnetospheres, starting from the classical model of Goldreich & Julian (1969), also argue that pulsar magnetosphere is filled with plasma. The sharpness of peaks in pulsar light curves, especially in gamma, naturally leads to the conclusion that emitting regions, and, hence, the regions where particles are being accelerated, are small and everywhere in the magnetosphere, except those small accelerating regions, the electric field is screened by dense plasma.

The vast majority of NS energy losses goes into the pulsar wind, the outflow of relativistic plasma which change the topology of the NS's magnetic field creating closed and open magnetic field lines zones. Plasma flow along open magnetic field lines starts at the NS surface and leaves the magnetosphere; that plasma must be constantly replenished. Even if charged particles can be extracted from NS surface, their number density would be several orders of magnitude lower than that inferred from observations of PWNe. Starting with the work of Sturrock (1971) the assumption about electron-positron plasma generation in pulsar polar caps has been an integral part of almost any pulsar model. It is also generally believed that pair creation is intimately connected to radio pulsar activity, as the death line – the place on the \( P - \dot{P} \) diagram where radio emission ceases – roughly corresponds to such pulsar parameters when the potential drop generated by NS rotation becomes smaller than the threshold for pair formation. Hence, production of electron-positron plasma in polar caps is a cornerstone of current pulsar “standard model”.

The problem of how plasma is generated in pulsar polar caps can not be considered separately from the problem of the global structure of the magnetosphere. Currents supporting the magnetosphere with its open and closed field lines zones flow along magnetic field lines all the way from the NS surface into the pulsar wind zone passing trough the plasma generating regions. Current density distribution is determined by the global mag-
netospheric structure and those small pair generation zones (which inductance is much smaller than that of the magnetosphere) must adjust to the current density imposed by the magnetosphere. Recently significant progress has been achieved in modeling of the global structure of pulsar magnetosphere (e.g. Contopoulos et al. 1999, Timokhin 2006, Spitkovsky 2006, Kalapotharakos & Contopoulos 2009), so the current density distribution in the magnetosphere is known. It has been explicitly shown (Timokhin 2006) that this current density distribution does not agree with assumptions about the current density used in than up to date quantitative “standard models” of polar cap plasma generation (e.g. Arons & Scharlemann 1979, Muslimov & Tsygan 1992, Daugherty & Harding 1982), which assumed stationary unidirectional plasma flow.

This discrepancy motivated me to start the study of pair plasma generation in pulsar polar caps which is free from assumptions about character of plasma flow and addresses the problem starting from first principles. The goal was to investigate how the pair plasma is generated when a given current density (set by the global magnetosphere structure) flows through the pair creating region. Here I give a brief overview of the first results of this study, described in more detail in Timokhin (2010) and Timokhin & Arons (2012), and discuss possible explanations for several phenomenas seen in pulsars.

2. Self-consistent numerical model of pair cascades

We assumed that pulsar magnetosphere is already filled with plasma and studied how this state is sustained†. In the reference frame corotating with the NS, the star’s rotation results in the effective background charge density, the Goldreich-Julian (GJ) charge density $\eta_{GJ}$. Existence of the open magnetic field lines requires these lines to be twisted; this twist must be supported by a certain current density $j_m$ which flows along the lines and through the cascade zone as well. Both these effects must be included in modeling of electrodynamics of the cascade zone, but almost all previous quantitative models of pair cascades did not include the inductive effects, i.e. they ignored $j_m$. We modeled how the cascade zone behaves under different current loads – in each simulation we required that a given current density $j_m$ flows through the cascade zone; in contrast to almost all previous works we studies the pair production when the current is fixed rather that the voltage.

We used a specially developed hybrid Particle-In-Cell/Monte Carlo (PIC/MC) numerical code which models electromagnetically driven pair cascades in truly self-consistent way, whereby particle acceleration, photon emission, propagation, pair creation, and screening of the electric field are calculated simultaneously (Timokhin 2009, 2010). As such truly self-consistent simulations had never been done before we started with the simplest possible model which, however, includes all types of physical processes relevant for pair formation in the polar caps of pulsars. Our model is one-dimensional, it includes curvature radiation as a gamma-ray emission mechanism and single photon absorption in strong magnetic field as a pair production mechanism. The electrodynamics takes into account the effects due to the GJ charge density $\eta_{GJ}$ as well as the current density $j_m$ imposed by the magnetosphere. The electrodynamics and plasma dynamics – particle acceleration and electric field screening by charged particles – are modeled by the PIC part of the code. Emission of gamma-rays, their propagation in magnetic field, and pair creation are modeled by the MC part of the code.

Boundary conditions implemented in the code included the case when particles cannot

† In other words, we did not study the (more difficult) problem of how the magnetosphere is formed.
leave the NS surface as well as the case of free particle outflow from the surface, the so-called Space Charge Limited Flow (SCLF) regime. The latter, less trivial case was modeled by creation of a pool of numerical particles just outside of computational domain at its NS’s end. The system was allowed to extract as many particles as it needed, in other words we allowed the cascade zone to set the electric field at the NS to zero self-consistently, without imposing it in the code manually. Particles were allowed to leave domain freely (if not prevented to do so by the electric field) and no particles were injected at the outer end of the domain.

3. Main results

We performed self-consistent simulations of pair cascades in pulsar polar cap in 1D for two most important classes of pulsar polar cap cascade models (i) when particles cannot be extracted from the NS surface (Timokhin 2010), the so-called Ruderman-Sutherland (1975; hereafter RS) model; and (ii) for currently the most popular model when particles can freely leave the surface (Timokhin & Arons 2012), the space charge limited flow regime, so-called Arons-Scharlemann (1979) model.

In both cases the cascade zone easily adjusts to any given current density \( j_m \) imposed by the magnetosphere provided the physical parameters allow for pair creation. This adjustments proceeds locally due trapping of some fraction of plasma particles by small fluctuating electric field. \( j_m \) turned out to be the most important parameter determining the efficiency of particle acceleration. In some cases sustaining if the imposed current density results in a flow with no particles acceleration and pair creation. If the imposed current density leads to pair formation, it always occurs non-stationary, a burst of pair formation is followed by a quiet phase when accelerating electric field is screened and no pairs are produced.

For the Ruderman-Sutherland model the cascade easily adjusts to the current density required by the magnetosphere and always produces dense electron-positron plasma in accordance with qualitative expectations of the original model, provided \( j_m \neq 0 \). Particle acceleration and pair production occur in form of discharges. At the beginning of each discharge cycle a gap (a charge starved spatial region) with accelerating electric field appears and grows in size until the potential drop across it becomes larger than the pair formation threshold. Particles accelerated in this gap emit pair production capable gamma-rays which inject electrons and positron into the gap, these secondary particles screen the electric field and destroy the gap. When the newly generated plasma leaves the domain the discharge starts anew. Surprisingly, the pair formation turned out to be very regular showing a limit cycle behavior, and gaps do not stay at the same place but move along magnetic field lines. The pair plasma has a thermalized low-energy component.

In the case of the space charge limited flow, however, the cascade behavior turned out to be qualitatively different from what was expected in “standard” cascade models. The character of the flow strongly depends on the ratio of the average current density flowing through the cascade zone to the GJ current density \( \eta_{GJ} c \), see Fig. 1. For field lines where the imposed current density is smaller that the GJ current density \( 0 < j_m/j_{GJ} < 1 \) (sub-GJ) no pair plasma is produced† because the accelerating zone is very small due to an instability of the plasma flow and a moderately relativistic electron low-density plasma (with the number density \( n = \eta_{GJ}/e \)) streams along those field lines. Pair formation is possible only along field lines where the current density is either larger

† in this regard our results support conjectures about the sub-GJ flow of Shibata (1997) and Beloborodov (2008)
Figure 1. Current density distribution in the polar cap of pulsar for different pulsar inclination angles $\alpha$ (central panel) and examples of particle distribution functions (as functions of particle momenta normalized to $m_e c$) for different cascade regimes in the space-charge limited flow model (top and bottom panels). Colors show the ratio of $j/j_{GJ}$ and the polar cap boundary is shown by a thin black circle on each subplot. Distribution function of electrons is shown by blue lines, positrons by red dashed lines, and gamma-rays by dotted black lines. Note that on the upper plot particles are only mildly relativistic and no pairs are produced (adapted from Timokhin & Arons (2012) with contribution of Xue-Ning Bai (Bai & Spitkovsky 2010)).

than the GJ current density $j_m/j_{GJ} > 1$ (super-GJ), or has the opposite sign to it $j_m/j_{GJ} < 0$, in regions with the return current. Pair creation is highly non-stationary, similar to discharges in the RS model. SCLF regime can sustain any imposed current density $j_m$ as well.

Contrary to expectations of previous models, the place where discharges occur is different for different flow regimes. For RS cascades with $j_m/j_{GJ} > 0$ discharges start close to the NS surface. For flows with $j_m/j_{GJ} < 0$ discharges start at the largest possible distance from the NS in both RS and SCLF regimes. For SCLF with $j_m/j_{GJ} > 1$ the position where discharges start depend on how the GJ charge density changes with the distance: discharges can start close to NS if the ratio $|\eta_{GJ}/B|$ ($B$ — magnetic field strength) increases with the distance from the NS, otherwise discharges start at large distances from the NS.

Discharges results in strongly fluctuating electric field, electrostatic waves. Fig. 2 shows an example of how the screening of the electric field in a discharge proceeds, there are 3 snapshots of a discharge in SCLF with $j_m = -0.5j_{GJ}$. Fluctuating electric field during
E and $\eta_{\pm}$ are plotted as functions of distance $x$ for the part of the calculation domain with intense pair formation. $x$ is normalized to the domain size $L$, $E$ normalized to the “vacuum” electric field $E_0 \equiv |\eta_{GJ}|/\pi L$, $\eta_{\pm}$ is normalized to the absolute value of the Goldreich-Julian charge density $|\eta_{GJ}|$. Time $t$ is measured in flyby time $L/c$.

discharge event has a power low spectrum, with long-wavelength (small $k$) cut-off moving to larger $k$ as the wavelength of fluctuations decreases. The phase velocity of such waves is larger than the light speed and they can not be effectively dumped via Landau damping.

4. Discussion

Results of these simulations imply that the pulsar magnetosphere is a much more complex physical system than it was assumed before. For the same pulsar period and magnetic field strength properties of plasma flowing along a given magnetic field line strongly depend on the value of the imposed current density $j_m$ along that line. Plasma properties (density, particle energy distribution) along different magnetic field lines can differ substantially due to non-uniform distribution of $j_m$ across the polar cap, and plasma content of magnetospheres in pulsars with different inclination angles will also differ as the current density distribution $j_m$ strongly depends on the inclination angle (see the middle panel of Fig. 1).

The locations of particle acceleration and emission zones depend in a non-trivial way on the pulsar inclination angle. For example, in the SCLF regime there is no pair plasma generation over the most areas of the polar cap in an aligned pulsar, but in an orthogonal rotator pair plasma is efficiently generated over the whole polar cap. Our results also indicate that magnetic field lines with the return current ($j_m/j_{GJ} < 0$) can have particle acceleration zones in the outer magnetosphere, as discharges tend to start at the furthest possible distance from the NS. This agrees with observations of pulsars with Fermi which indicate that gamma-rays are produced in the outer magnetosphere, in regions close to those where the field lines carrying the return current are expected to be.

Non-stationary discharges in flow regimes with pair creation incorporate time dependent, quasi-coherent currents on microsecond and shorter time scales. Such fluctuations might be a direct source of radio emission from the low altitude polar flux tube, a region strongly suggested as the site of the radio emission by the radio astronomical phe-
nomenology. The energy in such fluctuations is enough to power the radio emission and the spectrum of the fluctuations is a power law, consistent with radio phenomenology. Fluctuating electric field is also present in the domain the low energy flow with sub-GJ current density $0 < j_m / j_{GJ} < 1$ in SCLF regime, however, the amplitude of this field is so low that it is unlikely that these fluctuations could directly result in observable radio emission.

It is natural to assume that all these different flow regimes have different observational signatures, i.e. are responsible for different components in pulse profiles. If so, from the current density distribution (the central panel on Fig. 1) one can see that pulsar profiles should be roughly symmetric and the maximum number of separate emission regions should not exceeds 5, what seems to agree with results of phenomenological analysis of pulsar profiles (Rankin 1983).

Changes in $j_m$ could result in significant changes of pulsar emission. For example, in SCLF regime changing $j_m$ from super-GJ to sub-GJ will result in highly relativistic plasma flow becoming a low energetic one. If pulsar magnetosphere has a few metastable states with different current density distributions, then the character of radio emission could be qualitatively different in these two states; it could be that there will be no radio emission in one of the states state at all. This might be a low-level mechanism for nulling and/or mode changing in (at least some of) pulsars.

It must be said, however, that the resulting 1D model of the cascades is very simplified. Within the frame of 1D model many important issues cannot be addressed, such as influence of physical conditions at adjacent field lines on the accelerating electric field and excitation and propagation of electromagnetic waves. In SCLF regime the spatial scales involved are larger that the polar cap size, the characteristic transverse size of the system, what makes 1D model not suitable for accurate quantitative predictions. However, we expect that most of qualitative results obtained with the current model holds a multi-D treatment which will be reported in later papers.

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The structure of the pulsar magnetosphere via particle simulation with GRAPE

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Abstract. It is shown with a particle simulation that the outer gap can be reproduced under a few simple assumptions. The simulation includes just the first principles, namely Maxwell’s equations, a relativistic equation of motion with radiation drag, and electron-positron pair creation. We also suggest that the Y-point (the open-close boundary in the equator) is likely to be a place of heating and acceleration of plasma, and therefore it would cause high-energy emission. The dead zone along the separatrix of the oppositely directed current is found in the middle latitude region, which separates the outer gap and the polar cap accelerators.

Keywords. magnetosphere, plasmas, gamma-ray

1. Introduction

The outer gaps of the pulsar magnetosphere were theoretically suggested as a source of high-energy emission by Holloway (1973) around the null surface and by Cheng, Ho & Ruderman (1976) in view of the topology of the photon path. Recently, Fermi gamma-ray observations favor it as one of the dominant sources (see the review by Saz Parkinson, this volume). In this paper, we intend to examine the reality of the outer gaps via particle simulation.

2. Particle simulation

In our particle simulation, we assume axisymmetry and find a steady solution, so that Maxwell’s equations becomes Poisson’s equations for the electric potential and for the vector potential, which can be solved quickly by using GRAPE, the special-purpose computer for gravitational many-body problems, located at the National Astronomical Observatory of Japan. The plasmas in the magnetosphere are represented by several tens of thousands of super-particles. We iteratively solve the equation of motion for the particles and the electromagnetic field until a steady state is achieved. The calculation domain is three dimensional, in a cube with sides of 60 light-cylinder radii.

We take into account the radiation drag force in the equation of motion. The mass and the charge of the super particles are chosen so that the gyro radii are much smaller than the star. The time step is smaller than the shortest gyro period. Thus we follow any kind of drift motions.

The magnetospheric plasma is supplied in two ways. One is from the stellar surface if there is field-aligned electric field. If the electric field is screened, the emission stops, i.e., the condition of free emission on the stellar surface. The other is due to pair creation. Although conversion from the high energy gamma-ray into pairs should be treated, we simply assume that if the field-aligned electric field $E_\parallel$ at a given point is larger than a critical value $E_c$, the pairs are put there in a rate proportional to $|E_\parallel/E_c|$: on the spot approximation.
Figure 1. Particle distribution and magnetic field lines (solid curve) in the steady state. The dashed curves indicate dipole field.

Needless to say, the inner boundary for the electric potential provides electromotive force by the rotating magnet. This boundary condition is the source of all the magnetic activity and is strictly satisfied in our simulation because we use the Green function satisfying the boundary condition when we calculate the electric field.

We obtained the steady solution, in which the outer gap is formed and continuously produces electron-position pairs but still have the field-aligned electric field which is slightly larger than $E_c$, as shown in Fig. 1 (Wada & Shibata 2007). The pairs produced in the outer gap are immediately separated by sign of charge; positive particles go out toward the light cylinder while negative particles go back to the star (the polarity depends on direction of the magnetic moment to the rotation).

The gap formation is due to the charge deficiency compared to the Goldreich-Julian density needed to screen the magnetic-field-aligned electric field. This situation takes place because the pulsar has very strong electromotive force and therefore requires high charge density to screen out the field-aligned electric field, while the source of plasma is quite limited. This is relaxed by electron-positron pair creation. The charge deficiency is resolved by pair creation, and at the same time the poloidal current system completes. Thus even for the axisymmetric system, the rotating magnet can release rotational energy. In our simulation, pair creation steadily continues. Pairs can close the gap, so the field-aligned electric field and pairs can appear intermittently and alternatively.

The positive particles flow out across the closed magnetic field due to radiation drag drift, which is the back reaction of emission of angular momentum by photons. Because the mass is artificially enlarged in super particles, the size of this region is large in the simulation, in the actual magnetosphere flowing-out takes place in a thin current sheet. It is notable that the outer gap causes super-corotation beyond the outer gap (Wada & Shibata 2011).

The negative charges flowing back to the star charge it up, but this never continues, and emission of particles from the polar caps compensates, so that the system finally becomes in a steady state.
3. Y-point

Since the energy is provided by rotation, the centrifugal force plays a most important role. It is notable that azimuthal velocity at the top of the corotating dead zone approaches the speed of light, and the inertial mass diverges and breaks open the closed magnetic field. This effect is caused by the perpendicular electric field to the magnetic field, \( \vec{E} \times \vec{B} \), causing \( \vec{E} \times \vec{B} \)-drift motion in azimuthal direction.

It is interesting that the electric field larger than the magnetic field appears in a region around the equatorial neutral sheet beyond the light cylinder, as seen in Fig. 2 (Yuki & Shibata 2012). This is very much similar to the result of Uzdensky (2004) in his force-free model. The top of the closed field region, and beyond, is the transition region from the closed-open topology which can be one of the most active regions in the magnetosphere. In this region, strong acceleration by the electric field \( \vec{E} \times \vec{B} \) causes a jet outward along the equatorial plane. This is actually due to strong (relativistic) centrifugal force and a particular feature of the pulsar magnetosphere. Although this result is found in our steady solution, the jet could be quasi-steady with magnetic reconnection. We have made a particle-in-cell simulation to find quasi-periodic reconnection derived by centrifugal force at the top of the dead zone (Umizaki & Shibata 2010). We need further study for this region. The pulse shape from this region is quite difficult to predict because this shape is very sensitive to the dynamics, which are difficult to solve at the moment.

4. Current neutral dead zone

A new finding for the global structure is a dead zone in the middle latitudes elongating along a separatrix of the poloidal current (Yuki & Shibata, 2012). Thus we have two kinds of dead zone. One is the dead zone with closed magnetic field found in classical models. The new dead zone is located above the outer gap, and the poloidal current diminishes and reverses across the dead zone as seen in Fig. 2. The outer gap is sandwiched between the traditional dead zone with closed field region and this new dead zone, which may
Figure 3. Schematic picture of the axisymmetric magnetosphere found by the particle simulation. PC, SG and OG indicate the polar cap, slot gap and outer gap, respectively.

be called "current neutral dead zone", located in the middle latitudes. The accelerators in the polar caps and the slot gaps are located above the current neutral dead zone. Sometimes the slot gaps are reported to be below the outer gap. However, our simulation suggest that this is wrong and that the slot gaps are above the current neutral dead zone.

5. Future works

In future simulations, we need to take the following points in account:

(a) use realistic pair creation processes (not on the spot approximation),
(b) make larger numbers of particle to have a pulsar wind,
(c) use finer simulation particles so that the polar cap structure is resolved.

The computational requirements are the most serious problem. In Fig. 1, one can see that pairs are produced along the rotation axis. These pairs are not produced in the polar cap accelerator but just by fluctuating electric field because the resolution is not enough. If the number of particles were much larger, pair discharge such as obtained in Timokhin (2010) might take place.

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Pulsar electrodynamics revisited

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Abstract. The inductive electric field is unjustifiably neglected in most models for pulsar electrodynamics; it cannot be screened by the magnetospheric plasma, and it is not small in comparison with the corotation electric field. The perpendicular component of the inductive electric field implies a drift motion that is inconsistent with corotation at any angular velocity. Some implications of the inductive electric field and the associated drift motion are discussed.

Keywords. pulsars: general, plasmas, magnetic fields

1. Introduction

Pulsar electrodynamics, as developed four decades ago, includes some unresolved inconsistencies. The vacuum dipole model (VDM) is used for some purposes and the corotating magnetosphere model (CMM) is used for other purposes. Recent observational evidence for a link between magnetospheric phenomena (nulling, mode changing, timing noise) and the rate of slowing down (Kramer et al. 2006, Lyne et al. 2010) seems to require an explanation that involves features of both the VDM and the CMM. It is timely to consider how the incompatibility between the VDM and the CMM can be resolved.

In the VDM, the pulsar is modeled as an obliquely (angle $\alpha$) rotating magnetic dipole in vacuo. The energy and angular momentum are carried off by magnetic dipole radiation with a frequency equal to the rotation frequency of the star. The VDM is used to estimate the surface magnetic field, $B \sin \alpha \propto (P \dot{P})^{1/2}$, and the pulsar age, $P = 2 \dot{P}$, from the observed period, $P$, and period derivative, $\dot{P}$. In the CMM, it is postulated that the magnetosphere is corotating with the star, requiring that the electric field be the corotation field, $E_{\text{cor}}$, whose divergence determines the Goldreich-Julian charge density, $\rho_{\text{GJ}}$ (Goldreich & Julian 1969). As conventionally formulated, the CMM is quasi-electrostatic and quasi-stationary, due to assuming either an aligned rotator ($\alpha = 0$), or that the magnetosphere is stationary in the corotating frame. The CMM is the basis for most detailed models of the electrodynamics, in which $\rho_{\text{GJ}}$ can be provided by charges of one sign just above the stellar surface in the polar cap, but requires an additional source of charge, through pair creation in vacuum gaps (Ruderman & Sutherland 1975), at greater heights. Both the VDM and CMM are fatally flawed as stand-alone models.

Two unacceptable features of the VDM are that 1) the magnetic dipole radiation cannot escape because its frequency is below the plasma frequency (in the magnetosphere, the wind and the ISM), and 2) there is no plasma to emit the observed radiation. Two unacceptable features of the CMM are that 1) the logical consequence of the assumptions made in the CMM is a completely charge-separated (‘domed’) electrosphere (Michel 2004), and 2) quasi-stationary models are unstable to growth of large-amplitude electric oscillations when subject to temporal perturbations (Levinson et al. 2005, Beloborodov & Thompson 2007, Timokhin 2010).

The inductive electric field, $E_{\text{ind}}$, and the displacement current, $\varepsilon_0 \partial E_{\text{ind}} / \partial t$, are essential features of the VDM, and are ignored in the CMM. Including $E_{\text{ind}}$ involves a
substantial rethinking of pulsar electrodynamics. A self-consistent model needs to start from the VDM and incorporate the response (charge and current densities) of the plasma that modify the vacuum field, leading to a self-consistent field. We outline an EM/plasma model that includes this response, and identify some implications of the model.

2. Vacuum dipole and Corotating models

**VDM**: The exact form of the magnetic field for a rotating point dipole, \( m \), is

\[
B(t, x) = \frac{\mu_0}{4\pi} \left[ \frac{3x \cdot m - r^2 m}{r^5} + \frac{3x \cdot \dot{m} - r^2 \ddot{m}}{r^4 c} + \frac{x \times (x \times \dddot{m})}{r^3 c^2} \right], \tag{2.1}
\]

with \( \dot{m} = \omega \times m \), \( \dddot{m} = \omega \times (\omega \times m) \). The electric field is

\[
E(t, x) = \frac{\mu_0}{4\pi} \left[ \frac{x \times \dot{m}}{r^4} + \frac{x \times \dddot{m}}{r^2 c} \right]. \tag{2.2}
\]

These fields are included in the Deutsch (1955) model, which also includes a quadrupolar electrostatic field, due to \( E_{\text{cor}} \) inside the star implying a surface charge on the star.

Using labels dip = dipolar, ind = inductive, rad = radiative, with \( r_L = c/\omega \) the light cylinder radius, the magnetic field has terms \( B_{\text{dip}} \propto 1/r^3 \), \( B_{\text{ind}} \propto 1/r_L r^2 \), \( B_{\text{rad}} \propto 1/r_L^2 r \), and the electric field has \( E_{\text{ind}} \propto 1/r_L r^2 \), \( E_{\text{rad}} \propto 1/r_L^2 r \). Only the dipole term, which dominates at \( r \ll r_L \), and the radiative terms, which dominate at \( r \gg r_L \), are included in the conventional VDM. Here we emphasize the role of the inductive terms.

**CMM**: The corotation electric field is

\[
E_{\text{cor}} = -(\omega \times x) \times B, \quad \rho_{GJ} = \varepsilon_0 \text{div} E_{\text{cor}}, \tag{2.3}
\]

usually approximated by \( \rho_{GJ} = -2\varepsilon_0 \omega \cdot B_{\text{dip}} \). Thus, in the CMM the electric field is postulated, and Maxwell’s equations are used only to infer consequences (notably \( \rho_{GJ} \)) of this postulate. In contrast, in the VDM the rotating magnetic field is postulated, and Maxwell’s equations (with \( \rho = 0, J = 0 \)) are solved for \( E_{\text{ind}} \).

A prerequisite for assuming (2.3) and ignoring (2.2) is that the inductive field is either screened or is negligible. The latter is not the case: the ratio \( |E_{\text{ind}}|/|E_{\text{cor}}| \propto \sin \alpha \) is of order unity independent of \( r \). Screening is ineffective for the perpendicular component of \( E_{\text{ind}} \), and its neglect is not justified (except for \( \alpha \to 0 \)). When \( E_{\text{ind}} \) is included, the corotation postulate becomes untenable.

3. EM/plasma model

**Including plasma in the VDM**: An EM/plasma model may be identified by starting from the VDM and including the response of the plasma to the inductive electric field. This field is of low frequency, compared with other frequencies in the plasma. The simplest useful plasma model is the low-frequency limit of the response of a cold electron-positron gas. The cold-plasma model is used in a related application to auroral electron acceleration (Song & Lysak 2006), and although it is an oversimplification, e.g., the neglect of relativistic effects, an argument (given below) based on the polarization drift supports the use of the cold plasma approximation. The response to the components, \( E_{\text{ind}} \perp \) and \( E_{\text{ind}} \parallel \), perpendicular and parallel to the magnetic field, depends on the Alfvén speed, \( v_A \), and the plasma frequency, \( \omega_p \), respectively. We also include the effect of a conductivity tensor with components \( \sigma_\perp, \sigma_\parallel \).
After inverting the (temporal) Fourier transform, the relations implied by the cold-plasma response are

\[ J_\perp = \frac{c^2}{v_A^2} J_{\text{disp}} \perp + \sigma_\perp E_\perp, \quad \partial J_\parallel / \partial t = \varepsilon_0 \omega_p^2 E_\parallel + \sigma_\parallel \partial E_\parallel / \partial t, \quad (3.1) \]

where \( J_{\text{disp}} = \varepsilon_0 \partial E / \partial t \) the displacement current.

**Oscillatory parallel response:** The parallel response of the plasma is strongly oscillatory, as has been identified in the pulsar literature (Sturrock 1971, Levinson et al. 2005, Timokhin 2010). The resulting large-amplitude oscillations lead to pair creation, and the pairs can screen \( E_\text{ind} \parallel \).

**Perpendicular response:** It is impossible to screen \( E_\text{ind} \perp \) by charges. \( E_\text{ind} \perp \) can be screened by currents if these lead to a changing magnetic field that balances \( \partial B / \partial t \). This may occur inside the star, but is ineffective in a pulsar magnetosphere.

Including the perpendicular response (3.1) in Maxwell’s equations gives

\[ (\text{curl } B)_\perp = \frac{1}{v_A^2} \frac{\partial E_\perp}{\partial t} + \frac{1}{c^2} \frac{\partial E_\perp}{\partial t} + \mu_0 \sigma_\perp E_\perp. \quad (3.2) \]

Due to the strong field and low density in a pulsar magnetosphere, \( \sigma_\perp \) is small, and the final term in (3.2) can be neglected. (A collisional model for the conductivity gives \( \sigma_\perp \propto \nu_e \rightarrow 0, \sigma_\parallel \propto 1/\nu_e \rightarrow \infty \) for collision frequency \( \nu_e \rightarrow 0 \).) The strong field and low density also implies \( v_A^2 \gg c^2 \). The term involving \( 1/v_A^2 \) in (3.2) is then small compared with the term involving \( 1/c^2 \). Thus the plasma current is negligible in comparison with the displacement current. It follows that plasma does not modify \( E_\text{ind} \perp \) significantly from its vacuum value, where the displacement current balances curl \( B \).

**Inductively induced drift:** A perpendicular electric field in a magnetized plasma induces an electric drift in which all particles participate, irrespective of their charge. The important physical effect that is neglected by ignoring \( E_\text{ind} \perp \) is the inductive drift, \( v_\text{ind} = \mathbf{E}_\perp \times \mathbf{B}/B^2 \), or \( E_\text{ind} \perp = -v_\text{ind} \times \mathbf{B} \). This drift is of order the corotation speed times \( \sin \alpha \), and has all components, \( v_r, v_\theta, v_\phi \), nonzero (Melrose & Yuen 2012). The azimuthal component, \( v_\text{ind} \phi = 2\omega r \sin \alpha \cos \theta_m/(1 + 3 \cos^2 \theta_m) \), where \( \theta_m \) is the magnetic colatitude of the emission point, does not correspond to rotation at any angular speed (Melrose & Yuen 2012).

**Polarization drift:** The displacement current, due to the time-derivative of \( E_\text{ind} \perp \), induces a polarization drift. Electrons and positrons drift in opposite directions, leading to the polarization current, which reproduces the term \((c^2/v_A^2)(J_{\text{disp}})_\perp \) in (3.1), with \( v_A^2 \) defined to include relativistic effects. This alternative interpretation of (3.1) justifies the use of the cold-plasma model.

4. Implications of EM/plasma model

We mention four possible implications of the inclusion of \( E_\text{ind} \).

**Magnetosphere cannot be corotating:** Suppose that the inductive drift is superimposed on a corotation motion. The sign of \( v_\text{ind} \phi \) depends on the sign of \( \cos \theta_m \), where \( \theta_m \) is the magnetic colatitude. In a statistical sample of pulsars one expects half to have \( \cos \theta_m > 0 \) and half to have \( \cos \theta_m < 0 \). The implication is that, statistically, the source region in half of all pulsars would appear to be super-rotating, and half would appear to be sub-rotating.

**Subpulse drifting:** It may be that subpulse drifting is an observational consequence of this inductive drift. We are developing a detailed model; the first step is to identify the
values of $\alpha$ and $\theta_m$ that an observer whose line of sight is at angle $\zeta$ can see as a function of the phase, $\chi$, and the radius, $r$, of the emission point.

**Definition of the polar cap**: Conventionally, the boundary of the polar cap region is defined by the last closed field line, and there is no mixing of plasma across this boundary. However, the nonzero radial and polar components of $\mathbf{v}_{\text{ind}}$ imply that there is a plasma flow across the boundary, invalidating the concept of a well-defined boundary. This boundary is usually defined by retaining on $\mathbf{B}_{\text{dip}}$, and $\mathbf{B}_{\text{ind}}$ also needs to be included, for heights $r/r_L > 0.1$ say (Bai & Spitkovsky 2010). Thus the closed field region can be a source of plasma for the polar cap region.

**Acceleration of $\gamma$-ray emitting particles**: Screening of $E_{\text{ind}}^\parallel$ should occur provided sufficient charges are available. $\gamma$-ray emission is attributed to acceleration by $E_{\parallel}^\text{ind}$ in an outer (or slot) gap, where screening becomes ineffective due to charge starvation. The breakdown of screening causes $E_{\text{ind}}^\parallel$ to appear. Rather than acceleration being due to a putative electrostatic field across a gap (Takata et al. 2010), it is due to $E_{\text{ind}}^\parallel$ becoming (partially) unscreened and available to accelerate charges.

5. Conclusions

A viable (EM/plasma) model for pulsar electrodynamics needs to be fully electromagnetic and to include the response of the plasma to the EM fields. The first steps in formulating such a model is to start from the exact form, (2.1) and (2.2), of the fields for the VDM, and to include the plasma response to these fields, e.g., in the form (3.1).

The parallel plasma response is oscillatory, leading to pair creation (Levinson et al. 2005, Beloborodov & Thompson 2007, Timokhin 2010). The charges can screen $E_{\text{ind}}^\parallel$ in the inner magnetosphere. Breakdown of screening in the outer magnetosphere due to charge starvation plausibly accounts for acceleration of $\gamma$-ray emitting particles.

The perpendicular plasma response is ineffective in screening $E_{\text{ind}}^\perp$, implying an inductive drift that has not been included in existing models. The presence of the inductive drift, $\mathbf{v}_{\text{ind}}^\perp$, implies that the magnetosphere cannot be corotating, contrary to the central assumption in the CMM. The form of $\mathbf{v}_{\text{ind}}^\perp$ also implies a flow across the last closed field line, allowing plasma transfer between the “open” and “closed” regions. The possible interpretation of subpulse drifting in terms of $\mathbf{v}_{\text{ind}}$ is under investigation.

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Resistivity and dissipation in pulsar magnetospheres

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Abstract. Current models of pulsar magnetospheres typically assume either a complete absence of plasma or abundant ideal plasma filling the magnetosphere in order to compute the field structure. The latter condition is thought to be closer to reality; but we know of a number of pulsars in which the ideal conditions break down, resulting in dissipation and high-energy emission. In this work we formulate a resistive force-free scheme that allows us to consider the effects of resistive plasma and accelerating fields on the magnetospheric structure. We run numerical simulations to construct a family of resistive solutions that smoothly bridges the gap between the vacuum and the force-free magnetosphere solutions. We further provide a self-consistent model for the spin-down of intermittent pulsars, pulsars which appear to transition between radio-loud and radio-quiet states with different spin-down rates. Finally, we present models for high-energy emission from reconnecting current sheets in Gamma-ray pulsars.

Keywords. pulsars: general, gamma rays: theory, MHD, acceleration of particles

1. Introduction

Until very recently, quantitative solutions of the global pulsar magnetospheric structure existed only for the vacuum limit (Deutsch 1955) and for the limit of abundant plasma in force-free electrodynamics (see e.g., Contopoulos et al. 1999; Spitkovsky 2006). The real pulsar magnetosphere is likely operating somewhere in between these limits, with various accelerating gaps, regions of pair production, and strong current sheets likely causing local violations of the ideal MHD constraint, $\mathbf{E} \cdot \mathbf{B} = 0$. Knowing the structure of the magnetosphere, including such non-ideal effects, would be very useful for calculating the properties of pulsar emission. Indeed, currently the ideal force-free models that include the back-reaction of plasma currents on the field structure lack any accelerating fields by construction, and thus cannot be used to directly predict the spectra of gamma-ray radiation observed by the Fermi GST. Recently, we have developed a resistive force-free method that allows for variations in plasma supply and accelerating electric fields (Li et al. 2012a; see also Kalapotharakos et al. 2012). We specify an Ohm’s Law $\mathbf{j}' = \sigma \mathbf{E}'$ in the $\mathbf{E} \times \mathbf{B}$ drift frame of the massless plasma, representing a current sourced by relative counterstreaming of opposite charges along the magnetic field in this minimal velocity bulk fluid frame. This Ohm’s Law provides a closure for Maxwell’s Equations and allows us to construct a continuum of solutions transitioning between the vacuum and ideal force-free solutions as the conductivity parameter $\sigma$ is varied between 0 and $\infty$. The freedom in choosing the conductivity of the plasma further allows us to construct quantitative models for the spin-down of intermittent pulsars and explore the high-energy emission from $\gamma$-ray pulsars.
2. Intermittent Pulsars

A number of recently discovered “intermittent” pulsars switch between two distinct states: an “on”, radio-loud state, and an “off”, radio-quiet state. Spin-down rates in the two states differ by a large factor, \( \sim 1.5 - 2.5 \) (Kramer et al. 2006; Lyne 2009; Camilo et al. 2012; see also Lyne et al. (2010) for possibly related mode changing in radio pulse profiles). This is not easily understood in the context of current models since the force-free to vacuum spin-down ratio is always greater than 3. In Li et al. (2012b) we model the “on” state as a nearly ideal force-free magnetosphere with abundant magnetospheric plasma supply able to generate coherent radio emission. The lack of radio emission in the “off” state is associated with plasma supply disruption that results in lower plasma density on the open field lines. We model the “off” state using nearly vacuum conditions on the open field lines and nearly ideal force-free conditions on the closed field lines, where plasma can remain trapped even in the absence of pair production. Figure 1 illustrates magnetic field lines in the \( \mu - \Omega \) plane for these two states, both with 60° inclination angle. Color is representative of the out-of-plane magnetic field. The left panel, the “on” state, is a resistive solution taken at high conductivity, and is essentially force-free–like but with a spatially resolved current sheet. The right panel shows the “off” state, with high conductivity in the closed zone interior to the red contour, and low conductivity on open field lines exterior to the red contour.

![Figure 1. Magnetic fields in \( \mu - \Omega \) plane. Color is out-of-plane field. Left: Intermittent pulsar “on” state, highly conducting everywhere. Right: Intermittent pulsar “off” state, resistive on open field lines, highly conducting in closed zone.](image)

In the “off” state, current from toroidal advection of charged plasma in the closed zone leads to greater magnetic flux passing through the light cylinder and a larger fraction of open field lines than in the vacuum solution. Since open field lines carry Poynting flux, the “off” state spin-down is larger than the vacuum spin-down value. It turns out that the “off” state spin-down is a factor of \( \sim 2 \) higher than vacuum values for all inclination angles, and we naturally obtain a range of spin-down ratios between the “on” and “off” states, \( \sim 1.2 - 2.9 \), which corresponds to a likely range of pulsar inclination angles, 30°–90° (Li et al. 2012b).

3. Gamma-ray pulsars

Our resistive force-free method can spatially resolve the accelerating electric fields in the pulsar current sheet, offering the exciting prospect of explaining high-energy emission...
from the current sheet (e.g., Lyubarskii 1996). There is an ambiguity in determining particle velocities parallel to the magnetic field, however, as in all force-free methods, and we still have some freedom to choose particle velocities, especially in the current sheet. The characteristic double peaked γ-ray light curves suggest that particle motions in the sheet are nearly radially outwards, but possibly have a small toroidal component, representing angular momentum lost by the pulsar. At present it is not completely clear at what radial distance from the pulsar the γ-rays come from. We discuss two models for the γ-ray emission: near the light cylinder \( R_{LC} = c/\Omega \), and in the wind zone beyond a few \( R_{LC} \).

The primary argument in favor of γ-ray emission coming from near \( R_{LC} \) is that the available magnetic energy density decreases with radius, \( u_B = B^2/(8\pi) \propto 1/R^2 \). The observed interpulse bridge emission also arises quite naturally from particles flying along open magnetic field lines near the current layer, interior to \( R_{LC} \), as shown explicitly by Bai & Spitkovsky (2010). Emission from near the current sheet or the current sheet itself, beamed roughly in the radial direction, can give rise to a strong caustic in the skymap and double peaked light curves (Bai & Spitkovsky 2010; Arka & Dubus 2012).

We have explored a number of possible methods for producing this necessary beaming by studying microphysical processes operating in the current sheet (Li et al. 2012c, in prep). One possibility is that particles fly outwards along all open field lines and nearly radially outwards in the laboratory frame. Particles only emit near the current sheet or layer, however, where they become heated and can gyrate around magnetic field lines, radiating synchrotron photons radially outwards. Another possibility is that particles are ejected relativistically in plasmoids from local \( x \) points in the current sheet. Plasmoids will approximately follow the magnetic field direction on either side of the sheet, so they travel radially outwards away from the \( Y \)-surface in the laboratory frame. The accelerating electric field in the current sheet can also play an important dynamical role. The electromagnetic fields carry angular momentum, as the pulsar is spinning down, and the accelerating fields can drive particles in the current sheet in the toroidal direction. The strong γ-ray caustic will then be shifted to earlier phases closer to the radio emission, depending on the strength of the accelerating electric fields, in accordance with the observed light curves.

The wind zone beyond a few light cylinder radii offers an alternative solution (see e.g., Kirk et al. 2002; Petri & Kirk 2005; Petri 2011; Petri 2012; Li et al. 2012c, in prep), whose biggest advantage is that radial beaming of emission arises quite naturally. Beyond a few \( R_{LC} \), the force-free drift velocity (Bogovalov 1999) satisfies \( v_\phi/v_r = R_{LC}/R \), i.e., the velocity is directed radially outward, with wind \( \Gamma = \sqrt{1 + (R/R_{LC})^2} \). Any microphysical process driving particles to high transverse velocities along \( \vec{E} \) or \( \vec{B} \) in the wind frame will have transverse velocities suppressed by \( \Gamma \) in the observer frame, with maximum magnitude \( c/\Gamma \). Several authors have suggested that sufficiently high lorentz factors to generate GeV emission can be reached in the synchrotron radiation reaction limit, where reconnection heating balances synchrotron cooling losses (e.g., Uzdensky & Spitkovsky 2012).

Figure 2 gives the skymap and light curves when radiation is beamed in the radial direction from beyond 2 \( R_{LC} \), for 60° rotators and using the field solutions from our highly conducting force-free–like model. Radio emission occurs near \( \xi_{obs} = 60 \) and \( \phi = 0 \). The strong caustic essentially traces the shape of the current sheet on the skymap, accounting for light travel time delay effects. Strongly doubled peaked light curves will be seen for a range of observer angles, but two immediate questions stand out. First, there is no bridge emission, and it is unclear how to produce it in the wind zone, where
all the plasma is flying radially outwards at relativistic speeds. It may be necessary to produce this emission closer in to the light cylinder, where $\Gamma$ is smaller and beaming is less strong. A second issue is that in the wind zone it is more difficult to shift the caustic to earlier phases than closer in to the light cylinder, because toroidal particle velocities fall as $v_\phi \propto 1/R$ for constant angular momentum. A better understanding of microphysical reconnection processes in the wind frame may help to address both of these issues.

Figure 2. Skymap for wind zone model with emission from the current sheet beyond $2 R_{\text{LC}}$. Pulsar inclination angle is 60 degrees.

To summarize, we believe we have a good first order picture of the motions of $\gamma$-ray emitting particles in the context of reconnection models of high-energy emission. The observed light curves suggest that particles travel radially outward in the current sheets, with second order corrections to the velocities in the toroidal direction. Recently developed resistive methods give some hope for incorporating these corrections into microphysical reconnection models, and determining the radii at which emission occurs. Ultimately, particle-in-cell or magnetohydrodynamical simulations of the global pulsar structure, or the local current sheet physics, could provide additional information about particle acceleration and high-energy radiation.

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Modeling of pulsar magnetospheres

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Abstract. The inner workings of pulsar magnetospheres have fascinated and confused researchers since the discovery of pulsars. I will review the status of magnetospheric models, including vacuum, space-charge-limited and resistive force-free MHD. I will highlight model predictions for the integrated pulsar quantities (such as spin down and torques) and the observational consequences of calculated magnetic field structure. Particularly, high-energy emission from pulsars allows putting new constraints on the geometry of the emission region and the physics of particle acceleration in the magnetosphere.
Session 12

Emission mechanisms
Radio pulsar variability

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Abstract.

Pulsars are potentially the most remarkable physical laboratories we will ever use. Although in many senses they are extremely clean systems there are a large number of instabilities and variabilities seen in the emission and rotation of pulsars. These need to be recognised in order to both fully understand the nature of pulsars, and to enable their use as precision tools for astrophysical investigations. Here I describe these effects, discuss the wide range of timescales involved, and consider the implications for precision pulsar timing.

Keywords. pulsars: general

1. Introduction

A textbook pulsar emits a beam of radio emission from just above its magnetic poles. The mis-alignment of the spin and magnetic axes then results in a light-house effect as the star rotates. Those pulsars whose radio beams cut across the Earth are observed as a string of sharp pulses in the signals detected by radio telescopes. The signal is straightforward to model with a simple slow-down law consisting (usually) of just spin frequency, its derivative and (if applicable) some binary parameters. The regularity of the signal means that these pulses act as the ticks of an extremely precise clock. Furthermore, pulsars are often to be found in extreme environments, which we are able to study by utilising this clock-like nature. The moniker of ‘super clocks in space’ is well earned.

A real-life pulsar deviates from the ideal in a number of ways. This is due to a number of instrumental, propagation and intrinsic effects, many of which are not well understood. In § 2 we discuss the wide range of variable behaviour observed in pulsar signals. In § 3 we consider how pulsars actually work before asking why this is of interest to pulsar astronomers in § 4. Finally, in § 5, we present conclusions and discussions.

2. What do we see?

The range of variability timescales in pulsars is remarkably wide, spanning all timescales on which it has been possible to measure. The fastest timescales to have been probed are nanoseconds. The voltage signals from radio telescopes are commonly Nyquist-sampled at rates of ~ 1 GHz, but usually this time resolution is traded for frequency resolution, and furthermore data is integrated in time to increase the signal-to-noise ratio (S/N). However, in the case of the Crab pulsar this is not necessary in order to detect a signal, and Hankins et al. (2003) have observed kJy pulses lasting 2 ns, showing that its well-known ~ us ‘giant pulses’ are in fact composed of a large number of such “shots”. These shots appear to be the quanta of pulsar radio emission. They are not resolved — indeed, we might expect this, i.e. an intrinsic timescale of ~ 100 ps, given the uncertainty principle and the observations that pulsars emit over bandwidths of several tens of GHz (Maron et al. 2000; Camilo et al. 2007). The actual mechanism is unknown but the brightness...
temperature of \( T_B = 10^{37} \) K (for the Crab pulses) implies, using the well-known expression for the maximum possible brightness temperature \( T_{B,\text{max}} = 6 \times 10^9 N(\gamma - 1) \) K, a coherence factor of \( N \approx 10^{27} \). Clearly the mechanism is coherent, most likely involving particles emitting in bunches, a plasma instability or some kind of maser, but despite much effort (Ginzberg & Zheleznyakov 1970; Asseo et al. 1990; Lyutikov et al. 1999; Melrose 2004) the details are not known.

The duration of a time sample in most pulsar observations is usually \( \gg 100 \) ps so that a large number of shots are incoherently added within each time sample. The Poisson distribution of the shots then approaches that of a Gaussian, and it is common to model the pulsar signal as amplitude-modulated noise (Rickett 1975). This model is insufficient however, as single pulse studies show non-Gaussian variations on ms–ms scales, e.g. the “giant micropulses” seen in Vela by Johnston et al. (2001), and we see dramatic variations from one pulse period to the next, on ms–s scales, e.g. we see changes in intensity (by factors of \( \gtrsim 10^3 \)), phase, pulse shape and the number of components.

Extremely organised behaviour is seen on second to minute timescales, in the form of sub-pulse drifting. Here, a ‘Joy Division plot’ reveals that the pulses drift periodically (both earlier and later) in pulse phase in regular ‘bands’ as a function of time with typical repetition periods of tens of spin periods. A standard explanation for this behaviour has been the “carousel model” (Ruderman & Sutherland 1975) where disparate emission spots above the stellar surface are induced to rotate by \( E \times B \) drift. Lately however it has been shown that this model does not explain the drifting seen in PSR B0809+74 (Hassall et al., in prep.). In a study of 187 pulsars, using the Westerbork Synthesis Radio Telescope, Weltevrede et al. (2006) showed that at least one third exhibited drifting.

On timescales of seconds to minutes, and even up to hours we see further organised behaviour in the form of ‘moding’ — the changing of the pulse profile to one of a small number of different profiles. If there is no detected radio emission from one of these ‘modes’ the phenomenon is commonly termed ‘nulling’. A quantitative analysis of the pulse amplitude distributions of a large number of pulsars has recently been performed by Burke-Spolaor et al. (2012). This work looked at the single pulse statistics of 315 pulsars with detectable single pulses in the High Time Resolution Universe survey. The authors classify the pulse amplitude distributions as either Gaussian (7 sources, 2%), log-normal (84 sources, 27%), multi-peaked (18 sources, 6%) or unimodal (24 sources, 8%). Unfortunately the majority (182 sources, 58%) did not fit within these classifications. While we might suggest testing for more complex distributions for the unclassified sources, this is not possible due to a paucity of detected pulses. Of the unclassified 182 sources, only 92 had more than 20 detected pulses during the 9-minute survey pointings, and a single pulse was all that was detected for 22 of the sources.

Moding is also observed on timescales of hours to weeks, or even months. The first realisation of this came when Kramer et al. (2006) discovered that PSR B1931+24 is detectable as a radio pulsar only for periods of \( \sim 5 - 10 \) days before ‘turning off’ and remaining undetectable for \( \sim 25 - 35 \) days in a quasi-periodic fashion. Crucially this moding is accompanied by a \( \sim 50\% \) change in the spin-down rate, with \( \dot{\nu}_{\text{hi}}/\dot{\nu}_{\text{lo}} = 1.5 \). Since then two more “intermittent pulsars” have been reported — PSRs J1841–0500 (Camilo et al. 2012) and J1832+0029 (Lorimer et al. 2012). These sources have ‘on’ and ‘off’ timescales \( \sim 20 - 30 \) times longer than B1931+24 and spin-down rate ratios of 2.5 and 1.8 respectively. Lyne et al. (2010) presented results of several decades of Lovell Telescope observations of 17 pulsars where correlated quasi-periodic changes in \( \dot{\nu} \) and pulse profile were clearly observed. The changes in spin-down rate ranged from 0.3% to 13%. More examples of such behaviour continue to be identified (see e.g. Karastergiou, these
Table 1. An incomplete list of the variability and evolutionary timescales of a pulsar. A plethora of interstellar medium timescales also exist which will also modulate the observed pulsar signal, as well any gravitational wave sources. † Here we use the term ‘nulling’, but ‘moding’, ‘extreme pulse amplitude modulation’ or a variety of similar terms could be used interchangeably.

<table>
<thead>
<tr>
<th>Timescale</th>
<th>Name</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns</td>
<td>Radio quanta “shots”</td>
<td>Fundamental emission timescale</td>
</tr>
<tr>
<td>us−ms</td>
<td>Single pulse variations</td>
<td>?</td>
</tr>
<tr>
<td>ms−s</td>
<td>Pulse-to-pulse variations</td>
<td>?</td>
</tr>
<tr>
<td>s−min</td>
<td>Sub-pulse drifting</td>
<td>?</td>
</tr>
<tr>
<td>s−min</td>
<td>Nulling†</td>
<td>?</td>
</tr>
<tr>
<td>s−hrs</td>
<td>Extreme nulling</td>
<td>?</td>
</tr>
<tr>
<td>hrs−yrs</td>
<td>Quasi-periodic switching</td>
<td>Magnetospheric switching?</td>
</tr>
<tr>
<td>hrs−years</td>
<td>Orbital timescales</td>
<td>Orbital motion</td>
</tr>
<tr>
<td>∼10^7 yrs</td>
<td>NS cooling timescales</td>
<td>Thermal cooling</td>
</tr>
<tr>
<td>∼10^7 yr</td>
<td>Galactic Evolution, (G\rho_s)_W^{-1/2}</td>
<td>Moving in Galactic potential</td>
</tr>
<tr>
<td>10^5 − 10^7 yr</td>
<td>Spin Evolution, P/\dot{P}</td>
<td>Loss of rotational energy</td>
</tr>
</tbody>
</table>

3. How do they work?

Assuming that the propagation and instrumental effects can be understood (whether or not they can be removed) there are still a wide range of transient behaviours seen in pulsars. This leads us to a big question: How do we get erratic radio emission from a PSR with a particular timescale, and periodic switching?

For force-free magnetospheres (see below) it has been shown that a number of stable solutions exist with the closed magnetosphere not necessarily extending to the light cylinder radius (Contopoulos et al. 1990; Spitkovsky 2006). It has further been shown that perturbing these solutions can result in a rapid switch from one magnetospheric configuration to another (Contopoulos 2005). However, these perturbations are put in ‘by hand’ and the underlying reason for the switching remains unknown. Furthermore, why this would occur with a periodicity is unknown. That the switching is quasi-periodic,
Table 2. Some of the important questions regarding pulsar magnetospheres and the status of the force-free solutions (see e.g. Li; Spitkovsky, these proceedings).

<table>
<thead>
<tr>
<th>Question</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable magnetosphere with dE/dt &gt; 0?</td>
<td>Yes</td>
</tr>
<tr>
<td>Why force-free?</td>
<td>Don’t Know</td>
</tr>
<tr>
<td>2+ stable solutions possible?</td>
<td>Yes</td>
</tr>
<tr>
<td>Switching between configurations?</td>
<td>Mechanism unknown</td>
</tr>
<tr>
<td>Switching with (quasi-)periodicity?</td>
<td>No</td>
</tr>
<tr>
<td>Braking index predictions?</td>
<td>Many (n ≠ 3)</td>
</tr>
<tr>
<td>Radio emission explained?</td>
<td>No</td>
</tr>
<tr>
<td>Gamma-ray emission explained?</td>
<td>Realistic lightcurves</td>
</tr>
</tbody>
</table>

rather than strictly periodic, must also be explained. Recently Seymour & Lorimer (2012) have suggested that the quasi-periodicity resembles that seen on “the route to chaos” and detect chaotic behaviour in PSR B1828–11, one of the Lyne et al. (2010) sample. The timescales for the erratic behaviour are wide (see Table 1), so much so that it is difficult to see what the decisive variables are. If the moding is simply a result of the magnetospheric switching (Timokhin 2010) the timescales for both phenomena are obviously one and the same. This raises the question of whether pulsars with large pulse-to-pulse modulation on much faster timescales than the intermittent pulsars are changing magnetospheric configuration constantly. This would suggest a picture of highly unstable and frequent fast changes on the scale of the entire magnetosphere. If this is not what is occurring in these cases it is unclear on which timescales this ceases, as there seems to be a continuum of moding/switching timescales observed (Keane 2010a). We are forced to abandon our big question entirely in favour of a more tractable one: What does a PSR magnetosphere even look like?

There are two approaches to answering this question — the first is to solve Maxwell’s equations for a rapidly-spinning strongly-magnetic highly-conductive ball; the second is to try to determine the geometry of the system from observations of the polarisation characteristics of pulsar emission. Both of these approaches should result in the same answer, but both are fraught with many difficulties. Here I briefly describe the first approach, but refer the reader to the works of Radhakrishnan, Cooke, Kramer, Karastergiou, Johnston, Weltevrede, Rankin, Wright and Noutsos for information on the geometrical approach. When calculating Maxwell’s equations in the vicinity of the neutron star it is found that there are trapping surfaces for charges of opposite sign above the poles, and in the equatorial plane. Particles get ripped from the stellar surface and are simply trapped in these ‘electrospheres’ with no pulsar-like behaviour (see e.g. Fig. 2.4, Keane 2010b). One then would assume that either the initial conditions do not represent reality, i.e. in the violent supernova explosion wherein the neutron star was born there was abundant plasma provided from the offset so that the electrosphere scenario never arises, or, that the electrosphere solution is in fact unstable (e.g. to the diochotron instability, see Spitkovsky, these proceedings) and breaks down after some time. Regardless of the reason some authors have pressed on assuming “a sufficiently large charge density whose origin we do not question” (Contopoulos et al. 1999) and solved “the pulsar equation” (Michel 1973) for the first time. The results of this work show current flows in the magnetosphere coincident with the ‘gap regions’ for emission derived by the geometric approach so that it seems that progress is being made towards understanding pulsar magnetospheres. Table 2 summarises some of the knowns and unknowns.
4. Who cares?

“I don’t care, I just want to do timing.” Anonymous.

Some astronomers may not be very concerned with how pulsars actually work, and only interested in pulsars for their use as clocks, e.g. to use in pulsar timing arrays (PTAs). In this case the only question that matters is whether or not pulsar profiles are stable for typical PTA observations. Fortunately this can be measured, and one such method involves calculating \( \rho \), the cross-correlation coefficient of the observed pulse profile with a template profile. If \( 1 - \rho \propto N^{-1} \), where \( N \) is the number of periods folded into the observed profile, then the profile is stable (Liu et al. 2012). Longer integrations improve the profile’s S/N only and not its stability. While the value of \( N \) where the exponent transitions to \(-1\) denotes the stability timescale, different exponents reveal other timescales at work, e.g. milling/moding timescales if present (Keane 2010b). Although the stability of pulsar profiles is implicitly assumed† in pulsar timing, it is not clear whether this has been systematically confirmed for all PTA pulsars. The received wisdom is that \( 10^4 \) periods gives you a stable profile but Liu et al. (2012) found this to be dependent upon the pulsar with values of up to \( 10^5 \) periods required in some cases. It is important to note that a high S/N does not imply stability (based solely on S/N we can time pulsars using their single pulses, but this is not precision pulsar timing, see Keane et al. (2011) for details).

If one used pulsar profiles which were not stable then there would be no justification for expecting a good fit to the timing model, with \( \chi^2_{\text{red}} = 1 \). Oddly enough there is a practice (which is admittedly dying out) to assume that the best fit model, i.e. the one with the lowest \( \chi^2_{\text{red}} \) value, is the correct model, and to then scale the errors so as to make \( \chi^2_{\text{red}} = 1 \). The errors in this case are scaled by an ‘EFAC’ quantity. This is very bad practice for several reasons (see § 3.2.1 of Andrae (2010) for more details), e.g. it assumes that: the error distribution is Gaussian; the model is linear in all of its parameters; the model used is correct (also completely negating the point of using the chi-squared test).

Pulse jitter is another contribution to errors in pulse time-of-arrival measurements which is usually ignored. Jitter is only evident in pulsar profiles when the S/N of single pulses are \( \gtrsim 1 \). Currently, for PTA sources, this is only relevant for PSR J0437–4715. For SKA-era sensitivity this must be accounted for in all PTA pulsars, but fortunately this is possible, as has been demonstrated for J0437–4715 (Liu et al. 2012).

5. Conclusions & Discussion

Pulsar emission and rotation is variable on a wide range of timescales. It is vital to gain a full understanding of these things in order to (a) understand pulsars; and (b) perform precision pulsar timing. The author’s bias suggests to him that it may be difficult to achieve the latter with first making significant inroads into achieving the former. For example the observed behaviour (described in § 2) suggest a number of questions which the pulsar timing community should be thinking about: Is there any reason why there would not be (perhaps periodic or quasi-periodic) spin-down rate switching occurring in many/all pulsars? Is there any reason why there would not be (perhaps periodic or quasi-periodic) spin-down rate switching in many/all millisecond pulsars? Are there other (perhaps deterministic) timing instabilities yet to be identified? The planned upcoming studies of large pulsar timing databases (S. Johnston, private communication) will no

† It is assumed that the observed profile is a shifted scaled version of a smooth (sometimes analytic) template with additive noise.
doubt shed valuable light on what the answers to these questions are, and bring us a few steps closer to understanding those super clocks in space.

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References

Elementary radiation patterns in pulsar profiles

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Abstract. Highly symmetric double features observed in averaged pulsar profiles can be interpreted as the imprint of microscopic radiation beam characteristic of radiative mechanism operating in pulsar magnetosphere. The data put strong constraints on the possible radiation patterns, excluding entire classes of mechanisms, such as those based on parallel acceleration, or those that have complicated beams. Instead, several properties of double features (such as their symmetry, depth, shape, merging rate, large polarisation degree, and the association with bifurcated emission components) are consistent with the extraordinary-mode part of the curvature radiation beam. This shows that double notches are a clear signature of the curvature radiation process. We show that even with the emission process fixed, detailed modelling of double features remains a rather sophisticated and demanding task.

Keywords. pulsars: general, pulsars: individual (B1929+10, J0437-4715), radiation mechanisms: nonthermal

1. Introduction

Double absorption features (or: double notches) have so far been observed in integrated radio profiles of B1929+10 (Rankin & Rathnasree 1997), J0437−4715 (Navarro et al. 1997) and B0950+08 (McLaughlin & Rankin 2004). They are the peculiar ‘W’-shaped features observed in highly polarised emission. The separation Δ between the minima of the notches decreases with increasing frequency ν. They have a large depth of 20−50% (Perry & Lyne 1985; Rankin & Rathnasree 1997).

The notches have the symmetry characteristic for relativistic dipole radiation patterns. The basic model of this phenomenon assumes that each point of a laterally extended region locally emits a structured beam of radiation, with a shape determined by the type of radiative process. Hereafter, this angular distribution (directional pattern) of emitted radiation will be called a ‘microbeam’. The notches can be observed when our line of sight is passing through a localised, non-emitting part of this region (passage over a spot that is unable to emit detectable radiation).

2. Double notches as the probe of emission microphysics

The notches have fairly simple shape: they look like the letter ‘W’, which is mirror symmetric with respect to its centre (see Fig. 2). If the ‘W’ is interpreted as the shape of the microbeam, one has to reject any mechanisms which intrinsically produce microbeams of complicated shape. A neat example of such a model is the ‘curvature-drift-driven curvature-radiation maser’ in which only selected sub-parts of the usual (non-coherent) curvature radiation beam can be amplified. As shown by Luo & Melrose (1992), the absorption coefficient can become negative only within those parts of the beam (i.e. for only those directions within the beam), where emissivity decreases for increasing Lorentz
Figure 1. The principle of creating double features in radio pulse profiles: the line of sight traverses through a split-fan emission pattern, produced by outflowing particles that emit a double-lobed beam. Double notches are produced when a stream such as shown above is unable to emit any radiation, but is immersed in a laterally extended emission region.

factor $\gamma$. Thanks to the curvature drift, which inclines the beam further away from the plane of B-field lines when $\gamma$ increases, negative absorption can occur, but only within two sub-regions of the beam (see Fig. 1b in Luo & Melrose 1992). These amplified fragments of the beam are localised asymmetrically with respect to the symmetry plane of the noncoherent beam. They are therefore intrinsically asymmetric and cannot be associated with double notches.

The smooth and symmetric shape of double notches then tells us that whatever is the emission mechanism, it does not perform so drastic surgery on the beam’s shape, as in the case of the curvature drift maser. Instead, the striking resemblance to the textbook dipole radiation patterns suggests that the coherency mechanism amplifies the beam isotropically, preserving the original, non-coherent shape of the beam.

The angular distribution of dipole radiation from relativistic particles is considered in two limiting cases: when the acceleration vector $\vec{a}$ is parallel to, or perpendicular to, the charge velocity $\vec{v}$. In the case of $\vec{a} \parallel \vec{v}$ the beam has the obviously structured form of a hollow cone, with $\vec{v}$ along the beam’s axis. In the case of $\vec{v} \perp \vec{a}$, the beam can also exhibit a structure that may be attributed to the shape of double notches (see further below).

The parallel acceleration beam ($\vec{v} \parallel \vec{a}$) is emitted, for example, when longitudinal plasma (Langmuir) oscillations of frequency $\nu_p$ are inverse-Compton scattered by electrons with Lorentz factor $\gamma$. This type of a microbeam was initially thought to be associated with the double notches (Dyks, Rudak & Rankin 2007, hereafter DRR07). Though this idea has finally appeared incorrect, such a model was able to explain the observed merging rate of notches with increasing frequency: $\Delta \sim 1/\gamma \sim (\nu_p/\nu)^{1/2}$. In the case of a wide energy distribution of the scattering electrons, such a model produces intrinsically wide-band emission even from a localised spot in the magnetosphere, which is consistent with the frequency-independent location of double features in pulse profiles (lack of radius-to-frequency mapping, or RFM). Moreover, Lorentz factors of $\gamma \sim 10$, consistent with the measured separation of notches $\Delta \sim$ a few degrees, have been proposed in this model long before the notches have been discovered (Melrose 1978). Nevertheless, such a parallel-ICS model is considered to be not efficient enough to explain the observed large radio fluxes of pulsars, although numerical simulations seem to provide much stronger coherence than is achievable from analytical models (Schopper et al. 2002).

When confronted with the observed depth of double notches, the hollow-cone beam of the parallel-acceleration model fails definitely: the beam is unable to produce notches as deep as observed.

As shown in Dyks, Rudak & Demorest (2010, hereafter DRD10), the depth of modelled
notches is very sensitive to the topology of the assumed microbeam. In the case of the hollow-cone beam the minima of the notches are considerably back-lit by the surrounding area of laterally-extended emission region. This makes the notches very shallow, with maximum depth of a few per cent, to be compared with the observed value of more than 20% for B1929+10. This value has been determined thanks to the interferometric observations of Perry & Lyne (1985). For J0437−4715, with unknown zero-flux level in its averaged profile, only the upper limit of the depth is known, and estimated to \( \sim 50\% \).

This upper limit is close to the actual depth of double notches, if the minimum flux in the averaged profile of this pulsar is close to zero.

It has been shown in DRD10 that the depth approaching \( \sim 50\% \) results from the fact that the emission is intrinsically two-directional, or, that the beam emitted from any local point is double-lobed (Fig. 1). In such a case, at any pulse longitude the observer simultaneously detects radiation from two separate spots in a spatially-extended emission region. At the phase of a minimum in the notches, only one of the two places is non-emitting (or eclipsed), hence the 50% upper limit for the depth of notches.

The outflowing charges carry the double-lobed beam along the curved magnetic field lines (Fig. 1). This creates a split-fan-shaped beam with strong emissivity at a small angle to the plane of the stream, but with no emission strictly in the plane itself. The split-fan beam model of double notches is then supported by the observation of highly symmetric bifurcated emission components (BECs) in the pulse profiles of J0437−4715 and J1012+5307. In J0437−4715, double notches are actually observed in a trailing wing of a BEC (Navarro et al. 1997).

As shown in Fig. 1, detection of double features in pulsar profiles corresponds to the passage of sightline through the plane of the plasma stream. Therefore, the location of bifurcated features in pulsar profiles is frequency-independent. Double features are then useful to absolutely align profiles observed at different \( \nu \) (see figs. 1 and 2 in DRD10). This can be used to precisely determine dispersion measure.

In the case of the curvature radiation (\( \vec{a} \parallel \vec{v} \)) the beam can be decomposed into two parts: one which is polarised orthogonally to the plane of electron trajectory and the remaining part, polarised parallel to this plane. In pulsar plasma, only the orthogonally-polarised part (X-mode) can reach the observer, whereas the remaining ordinary-mode part is suppressed and damped (Asseo, Pellat & Sol 1983; Arons & Barnard 1986). The extraordinary-mode part of the curvature radiation beam has several properties...
consistent with the observed properties of double notches: it has the much needed, double-lobed, and plane-symmetric shape, which allows us to explain the large depth of notches. The beam narrows with increasing frequency at a rate which is consistent with the observations. In the case of the curvature radiation (CR), the angular separation $\Delta$ between the peaks of the beam, varies as $\Delta \propto \nu^{-1/3}$, or $\Delta \propto \nu^{-1/2}$, depending on whether the low-frequency, or high-frequency part of the spectrum is observed (Jackson 1962). This roughly corresponds to the observed merging rate of double features (see Fig. 7 in Dyks & Rudak 2012, hereafter DR12).

The extraordinary part of the curvature microbeam successfully reproduces the shape of double notches in the pulse profile of B1929+10. Fig. 2a presents such a fit when no account for the non-zero width of the stream is done. The asymmetry of the notches is attributed to the oblique cut through the stream. When the central maximum of the ‘W’ is lowered down to mimic the finite width of the stream (Fig. 2b) the quality of the fit reaches $\chi^2/dof = 0.7$ and 0.2 for the left- and right-hand notches, respectively (see DR12 for more details).

The intrinsic size of the X-mode CR beam is $2\psi = 1.72^\circ (\rho_6 \nu_9)^{-1/3}$, where $\rho_6$ is the curvature radius of electron trajectory, and $\nu_9$ is the frequency in GHz. The apparent size of the beam, measurable as the observed separation of peaks/dips, can be approximated with the formula: $\Delta \approx 2\psi/(\sin \zeta \sin \delta_{cut})$, where $\zeta$ is the viewing angle between the rotation axis and the line of sight, whereas $\delta_{cut}$ is the ‘cut’ angle at which the sightline traverses through the split-fan beam (see Fig. 2 in DR12). The apparent $\Delta$ can then be magnified by the well-known effect of ‘not a small angle’ ($\zeta \ll 90^\circ$) as well as because of the oblique passage through the beam ($\delta_{cut} \ll 90^\circ$). For statistically-average values of $\zeta = 60^\circ$ and $\delta_{cut} = 45^\circ$, the separations measured at 1 GHz suggest that most of double features corresponds to $\rho_6$ between 0.3 and 1 (see Fig. 3). This is the curvature of dipolar B-field lines in the closed field line region: for the neutron star radius of $10^6$ cm, the smallest $\rho$ available in dipolar magnetosphere of every pulsar is equal to $3.3 \times 10^5$ cm, whereas the surface value of $\rho$ in the region emitting at a right angle with respect to the dipole axis is $8.7 \times 10^5$ cm. Some double features are located far from the main pulse of the profile, which is also consistent with emission from the closed field line region.
Figure 4. A zoom into averaged pulse profiles of B1929+10 at three different frequencies (all lines present the total flux). Because of narrowing of the non-emitted beam, the clearly double feature at 327 MHz (pulse phase 103.5°) evolves into a single feature at 1.5 GHz.

The pulsar J1012+5307 has an exceptionally wide bifurcated emission component (BEC) which requires that at least one of the viewing parameters is very small (see the dashed line in Fig. 3, calculated for ζ = 60°, δ_{cut} = 15°).

3. Complexity of modelling of double features

The shape of double features can well be reproduced exclusively by the shape of the microbeam, provided the beam is much wider than the non-emitting stream (or the emitting stream, in the case of bifurcated emission components). This is roughly the case shown in Fig. 2. At increasing frequency ν, the microbeam becomes narrower and may become comparable to the stream’s width. The resulting shape is then a convolution of the microbeam shape with the profile of plasma density/emissivity across the stream. Numerical simulations show that because of such convolution, the flux at the central maximum in double notches decreases, and the ‘W’ transforms into a single, U-shaped feature. This qualitatively explains the frequency evolution of double notches in B1929+10 (see Fig. 4).

The necessity of the convolution of the beam with the stream profile is just one of several difficulties that need to be taken into account to model double features properly. The second problem is that for an oblique passage through the split-fan beam, double features look generally asymmetric (see fig. 2 in DR12). The degree of this asymmetry is frequency-dependent in the presence of the RFM, i.e. when the minima (or maxima) of emissivity occur at a ν-dependent height. Double features are then symmetric only at a specific ‘frequency of symmetry’ ν_{sym}, whereas they look asymmetric at ν ≠ ν_{sym}. This phenomenon may be responsible for a slight asymmetry of notches shown in Fig. 2. Such oblique-cut asymmetry also explains the frequency evolution of the pronounced, bifurcated emission component in the profile of J1012+5307 (fig. 5 in Kramer et al. 1999; for more details see DR12). Therefore, to fit double notches precisely, it is required to model full 3D geometry of emission stream, with adjustable parameters describing the RFM law, r-dependence of ρ, and adjustable cut angle δ_{cut}.

Some complexity is related directly to the model of the microbeam itself: even for a precisely selected frequency ν (with infinitely narrow bandwidth) the shape of outer wings of the CR microbeam varies slightly with electron energy γ. To find a net shape of the beam it is then necessary to integrate over the electron energy distribution. This makes the number of fitting parameters even larger.

Last but not least, the physical model of the curvature microbeam can be improved, by using the curvature radiation pattern for a charge moving in electron-positron plasma.
Several properties of this ‘charge in plasma’ beam are similar to the properties of the orthogonally polarised part of the vacuum beam, e.g. the double-lobed form with no emission within the plane of trajectory, or $\nu$-dependence of the beam size. However, the shape of this pattern is somewhat different from the orthogonally polarised part of the vacuum beam, which has been used in Fig. 2. This is because the wave induces additional current in the plasma, which modifies the wave equation with respect to the vacuum case. A clear, easy-to-follow derivation of differential equation that describes this beam shape is given in Gil, Lyubarsky & Melikidze (2004). It will be interesting to use this version of the beam in future modelling efforts.

4. Conclusions

Bifurcated emission features observed in averaged radio profiles must be created by the passage of sightline through elongated, split-fan-shaped beams of emission (as opposed to hollow cone beams). Bifurcated ‘absorption’ features (double notches) are created in a similar way: through observation of an elongated, double ‘absorption’ structure with geometry similar to the split-fan emission beam.

This interpretation implies that apparently multiconal profiles of some pulsars (e.g. the millisecond PSR J0437$-4715$) actually have spoke-like geometry, with the radiating streams diverging away from the magnetic dipole axis. This explains the lack of RFM in such pulsars, as well as the indentations (dips) at the peaks of such ‘not-really-conal’ components.

Curvature radiation is a mechanism which intrinsically emits the beam with appropriate properties: double-lobed, narrowing with increasing frequency, and limited to a single polarisation mode, with the latter property consistent with the very large polarisation degree of double features. Therefore, double notches can be considered as a paramount signature of curvature radiation operating in pulsar magnetosphere.

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References

Pulsars in gamma rays: What Fermi is teaching us

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Abstract. The 2nd Fermi-LAT pulsar catalog includes 117 γ-ray pulsars, of which roughly one third are millisecond pulsars (MSPs) while the remaining two thirds split evenly into young radio-loud and radio-quiet pulsars. Although this large population will enable future, detailed studies of emission mechanisms and the evolution of the underlying neutron star population, some nearly-universal properties are already clear and unequivocal. We discuss some of these aspects below, including the altitude of the γ-ray emission site, the shape of the γ-ray spectrum, and the implications of the latter for the radiation mechanism.

Keywords. pulsar: general, gamma rays: observations, radiation mechanisms: nonthermal

1. Introduction

Since their discovery forty-five years ago (Hewish et al. 1968), pulsars have primarily been studied at radio wavelengths—a natural consequence of their discovery mode and the progression to ever larger antennae and higher-bandwidth receivers. Yet pulsars emit only a tiny fraction (\(\sim 10^{-5}\)) of their spindown luminosity \(\dot{E}\) at radio wavelengths. Furthermore, their high brightness temperature and variability on timescales as short as a few ns (Hankins et al. 2003) indicate a coherent emission process from a small volume. Making inferences about the global structure of the pulsar magnetosphere from such local measurements is difficult.

Young pulsars and MSPs, however, are extraordinarily efficient sources of γ rays, converting 1–100\% of their spindown luminosity into 100 MeV–30 GeV emission (e.g. Abdo et al. 2010b, and noting that efficiencies can be highly uncertain due to anisotropic beams and distance uncertainty). The emission is incoherent, and such efficiency implies much of the potential induced by the pulsar’s magnetic field is involved in particle acceleration, i.e. the acceleration and emitting volumes are large on the scale of the magnetosphere. Moreover, the ultrarelativistic particles powering the γ emission propagate along magnetic field lines and beam their emission along them. Thus, γ rays are a tracer of the large scale magnetic field structure.

Prior to the Fermi Large Area Telescope (LAT), only a handful of γ-ray pulsars were known, primarily of the young, radio-loud class, limiting their usefulness in studies of the magnetosphere and the underlying pulsar population. The situation evolved rapidly after the successful launch of Fermi, with the discovery of γ-ray emission from MSPs (Abdo et al. 2009a) and radio-quiet young pulsars from fecund “blind” searches of the LAT data (Abdo et al. 2009b). The first Fermi pulsar catalog (Abdo et al. 2010b) provided properties of 46 γ-ray pulsars, an appreciable increase in number and diversity. The second Fermi pulsar catalog (2PC), in preparation, includes 117 γ-ray pulsars and more sophisticated analysis. For instance, light curves use photon weights (Kerr 2011) which
provide increased S/N and a reliably-estimated background level. In-depth spectral analyses attempt to disentangle magnetospheric emission from astrophysical backgrounds, including pulsar wind nebulae.

2PC will undoubtedly fuel detailed population (synthesis) studies. The breadth and depth of the observed population, however, suggest that any observed trends are nigh-universal properties of γ-ray pulsars and are worth studying in their own light. Below, we detail two such trends. First, γ-ray emission appears to originate in the outer magnetosphere. Second, the spectral properties of the emission, for all pulsars save the Crab, are consistent with curvature radiation.

2. γ-ray emission altitude
The height in the magnetosphere from which the bulk of γ-ray emission arises is probed through several mechanisms. The first, relatively model-independent method, depends on the altitude-dependent opacity for pair production by γ-rays on the strong magnetic field near the surface of the neutron star. Two additional methods depend on the assumed structure of the magnetic field, but with little sensitivity to the details. Below, we briefly discuss each method.

2.1. Magnetic opacity
In strong magnetic fields, classically forbidden processes, such as one-photon pair production and annihilation, become allowed (e.g. Harding 1991). The former process, in particular, attenuates high-energy γ rays. The altitude by which the magnetic field has weakened sufficiently to allow photons of energy $E$ to escape is given by $r \approx (B_{12} E/1.76 \text{ GeV})^{2/7} P_{17}^{1/7} R_{*}$ (Baring 2004) with $B_{12}$ the magnetic field in units of $10^{12}$G and $R_{*}$ the neutron star radius. The observation of photons well above 10 GeV for young neutron stars implies production above a few $R_{*}$. Although this constraint is small in

![Figure 1. The period (P) and period derivative (dP/dt) of 2PC pulsars.](image-url)
terms of the distance to the light cylinder, $R_{\text{LC}}$ (which depends on period, but for young pulsars is $\sim 200-2000 R_\star$), it rules out emission from particles accelerated near the polar cap (e.g. Arons and Scharlemann 1979).

Additional evidence along these lines stems from the shape of the spectral cutoff observed in Fermi pulsars. Since the opacity to magnetic attenuation depends on energy, the curvature radiation spectrum from low-altitude photons is suppressed superexponentially. The observed spectra, however, show no such suppression. Indeed, as discussed below, they typically decay subexponentially; see, e.g. the spectra of Geminga (Abdo et al. 2010a) and Vela (Figure 3).

2.2. Caustics

Although observations of high energy ($\gg 1$ GeV) photons and gradual spectral cutoffs rule out emission from near the stellar surface, they do not help to distinguish between “low altitude” (10–30% of $R_{\text{LC}}$) and “outer magnetospheric” (OM; >30%$R_{\text{LC}}$) origin. These definitions are somewhat arbitrary, and another convenient division between low altitude and OM emission is the null charge (NC) surface, where the magnetic field projected along the spin axis vanishes. Indeed, the NC surface is the traditional starward edge of the eponymous “outer gap” of such particle acceleration models (e.g. Cheng, Ho, and Ruderman 1986). Other models, such as the slot gap (e.g. Muslimov and Harding 2003), predict emission both above and below the NC surface.

A general property of emission from the OM is the formation of caustics from near cancellation of relativistic aberration, time of flight across the magnetosphere, and field line sweepback (Morini 1983). The degree of sweepback determines the precise location in the magnetosphere for caustic formation, but static, vacuum, and force-free MHD magnetic field solutions all demonstrate such features, as shown e.g. by Romani and Yadigaroglu (1995), Watters et al. (2009), and Bai and Spitkovsky (2010), respectively. In the population of young 2PC pulsars, caustic-like peaks are a nearly universal light curve feature, a clear indication of OM origin.

For radio-loud pulsars, two important quantities may be estimated: $\delta$, the phase lag from the magnetic axis to the first $\gamma$ peak, and $\Delta$, the separation of (if present) the two primary $\gamma$ peaks. Generally, OM magnetosphere and emission models predict a correlation of these two quantities, with the shape depending on the model details. The observed correlation of 1PC agrees roughly with “outer gap” models (see e.g., Watters et al. 2009) and the correlation is strengthened for young pulsars in 2PC. The precise phase relation is a sensitive probe of the structure of the magnetosphere and may reveal, e.g., the extent to which currents shape the magnetosphere. MSPs show a similar, though more scattered, correlation, with some exceptions. These are “aligned” MSPs (e.g. PSR B1937+21, see Guillemot et al. 2012) whose $\gamma$-ray and radio emission occur at the same rotational phase, inviting speculation that both beams originate from the same OM caustics.

2.3. Unpulsed magnetospheric emission

A final argument for the dominance of OM $\gamma$-ray emission is the general absence of unpulsed emission—that is, emission present throughout all rotational phases. The level of such emission is robustly estimated in 2PC through the use of photon weights; these weights are derived directly from the phase-averaged spectral model, which accounts for the spatial distribution of astrophysical backgrounds. In contrast, background levels in 1PC were estimated by considering photon counts in an off-pulse annulus around the pulsar, subject to substantial inaccuracy from spatial variation in the background level.

In the altitude range above the polar cap but below the outer magnetosphere, the divergence of field lines causes beams from the open zone to illuminate an ever greater
fraction of the sky with increasing altitude, leading to emission with little modulation at sufficiently high altitudes. At even higher (OM) altitudes, caustics begin to form, leading to anisotropic and fully-pulsed emission. Thus, the presence of unpulsed magnetospheric emission is a sensitive indicator of emission from low altitudes.

In the 2PC, only two pulsars (PSRs J1836+5926 and J2021+4026) have levels of unpulsed emission competitive with or exceeding modulated emission, while the remaining pulsars show subdominant or absent off-peak emission, suggesting that emission from low altitude plays a minimal role in most $\gamma$-ray pulsars.

3. $\gamma$-ray emission mechanism

A second question 2PC is poised to answer is the nature of the dominant $\gamma$-ray radiation mechanism. The simplest, and arguably most widely favored, process for producing the GeV photons is curvature radiation from leptons with Lorentz factors of $\sim 10^7$ flowing along magnetic field lines. The primary alternative is inverse Compton emission, potentially from synchrotron seed photons (synchrotron/self-Compton). A detailed review of these models is beyond the scope of this paper.

The primary discriminator between the two mechanisms is the spectral shape of the broadband emission. While a few bright pulsars are detected in hard X-rays and soft $\gamma$ rays, the LAT GeV spectrum is the primary observable. Although the expected spectral shape is a complicated function of the acceleration and cooling of the emitting particles, the spectral cutoff for curvature radiation is cleanly determined by the highest-energy particles, and the absence of a strong cutoff could be interpreted as evidence for IC emission. However, as we show below, two effects—one technical and one physical—confound such simple conclusions, and the vast majority of Fermi pulsar emission is consistent with curvature radiation.

3.1. Monoenergetic spectrum

The curvature radiation spectrum of a single particle is set by the particle energy and the radius of curvature of the magnetic field. This monoenergetic photon spectrum, summed over polarizations, takes the simple form (Jackson 1998)

$$\frac{dN}{dE} \propto \int_{E/E_c}^{\infty} K_{5/3}(x) \, dx,$$

where $K$ is a modified Bessel function. In the limits $E \ll E_c$ and $E \gg E_c$, the spectrum asymptotes to the well known forms $dN/dE \propto E^{-2/3}$ and $dN/dE \propto E^{-1/2} \exp -E/E_c$, respectively. Typical measured and expected values of $E_c$ of 1–3 GeV fall squarely in the middle of the LAT passband. The functional form most often used to fit LAT spectra, $dN/dE \propto E^{-\Gamma} \exp -E/E_c$ (PLEC), can only mimic one or the other of these two limits. Thus one must be cautious in interpreting a failure of the PLEC model to fully describe the data as a failure for the curvature radiation mechanism.

We briefly probe the magnitude of the error made in approximating a monoenergetic curvature spectrum with the PLEC model. In Figure 1 (left), we show the monoenergetic photon spectrum with $E_c = 2$ GeV. The PLEC spectrum that most closely agrees at energies $E \ll E_c$ with the exact curvature spectrum has $\Gamma = 0.7$, close to the expected asymptotic value 2/3. However, this photon index is softer than the high-energy value of 1/2, causing the PLEC model to appreciably underestimate the monoenergetic spectrum for $E > E_c$, resulting in a discrepancy of $\sim 20\%$ at 20 GeV (Figure 1, right). Such energies are well within reach of the LAT, and indeed the observed spectra of bright pulsars such as Vela show a disagreement of just such a magnitude. These conclusions are in line with
those of the phase-resolved spectroscopy of Abdo et al. (2010c) where spectra in narrow phase windows agree well with a PLEC model.

3.2. Spectral superpositions

An even more drastic effect stems from the caustic nature of OM emission. Because emission piles up over a large volume of the magnetosphere, multiple field lines / radii of curvature are expected to contribute to the phase-averaged spectrum. For a constant accelerating electric field, this leads to a linear spread in $E_c$. In Figure 1 (left), we show a mixture of 10 spectra with $E_c$ uniformly distributed from 1 to 3 GeV. The low energy (approximately power law) portion of the spectrum is essentially unchanged from a monoenergetic spectrum with the mean $E_c = 2$ GeV, while the portion above 2 GeV

![Figure 2](image)

**Figure 2.** *Left:* A monoenergetic ($E_c = 2$ GeV) curvature radiation spectrum is shown in solid blue, along with a PLEC model that agrees closely with it below $E_c$ (dashed red). A mixture of monoenergetic spectra appears in dot-dashed green. *Right:* The ratio of monoenergetic spectra to a PLEC approximation. A single spectrum ($E_c = 2$ GeV) appears in solid blue, while the mixture spectrum described in the text is shown in dashed green.

![Figure 3](image)

**Figure 3.** The 2PC phase-averaged spectrum of PSR J0835-4510 (Vela). The best fit PLEC is shown as the solid, red line and substantially underestimates the observed spectrum.
is much harder than the single $E_{\gamma} = 2$ GeV spectrum. Figure 1 shows that in the case of this modest mixture the simple PLEC model can underestimate the spectrum above 10 GeV by an order of magnitude at the highest energies accessible to the LAT.

4. Conclusions and the future

In summary, the dramatically increased size and breadth of the $\gamma$-ray pulsar population is finally settling some of the longstanding questions about the origin and mechanism of $\gamma$-ray emission. We now know that $\gamma$ rays arise primarily from the outer magnetosphere, and that the spectral signature is consistent with electrons and positrons emitting curvature radiation. Moreover, because $\gamma$ rays are such an excellent tracer of the magnetosphere, detailed analysis of the Fermi light curves and spectra offer the opportunity to test more sophisticated emission theories and probe the magnetosphere structure in model-independent ways.

Although the trends discussed above are nearly universal, the few exceptions also offer tantalizing opportunities for better understanding of the pulsar machine. The recent detections by VERITAS and MAGIC (e.g. Aliu et al. 2011, Aleksić et al. 2011) of pulsed photons through energies $\gtrsim 100$ GeV from the Crab pulsar imply at least some of the Crab’s $\gamma$-ray emission originates from inverse Compton scattering (see e.g. Lyutikov, Otte, and McCann 2012). Indeed, of all pulsars detected above 100 MeV, only the Crab peaks in $\nu F_{\nu}$ well below 1 MeV, indicating the presence of a strong synchrotron component and motivating a synchrotron/self-Compton (SSC) picture for $\gamma$-ray emission. Discovery and analysis of “transition” objects such as PSR B1509-58, whose $\nu F_{\nu}$ peak is of order 1 MeV (Kuiper et al. 1999, Pilia et al. 2010, den Hartog et al. in prep), may shed light on the transition, if any, from a SSC-dominated radiation mechanism to a curvature-dominated one.

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Binary pulsar B1259-63 spectrum evolution: detailed study

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Abstract. We studied the radio spectrum of PSR B1259-63 in an unique binary with Be star LS 2883 and showed that the shape of the spectrum depends on the orbital phase. We proposed a qualitative model which explains this evolution. We considered two mechanisms that might influence the observed radio emission: free-free absorption and cyclotron resonance. Recently published results have revealed a new aspect in pulsar radio spectra. There were found objects with turnover at high frequencies in spectra, called gigahertz-peaked spectra (GPS) pulsars. Most of them adjoin such interesting environments as HII regions or compact pulsar wind nebulae (PWN). Thus, it is suggested that the turnover phenomenon is associated with the environment than being related intrinsically to the radio emission mechanism. Having noticed the apparent resemblance between the B1259-63 spectrum and the GPS, we suggest that the same mechanisms should be responsible for both cases. Therefore, the case of B1259-63 can be treated as a key factor to explain the GPS phenomenon observed for the solitary pulsars with interesting environments and also another types of spectra (e.g. with break).

Keywords. pulsars: general, individual (B1259-63) - stars: winds, outflows - ISM: general, magnetic fields - radiations mechanism: non-thermal

1. The gigahertz-peaked spectra pulsars

Generally, the observed radio spectra of most pulsars can be modelled as a power law with negative spectral indices of about -1.8 (Maron et al. 2000). If a pulsar can be observed at frequencies low enough (i.e. 100-600 MHz), it may also show a low-frequency turnover in its spectrum (Sieber 1973; Malofeev et al. 1994). On the other hand, Lorimer et al. (1995) mentioned three pulsars which have positive spectral indices in the frequency range 300-1600 MHz. Later, Maron et al. (2000) re-examined spectra of these pulsars taking into account the data obtained at higher frequencies (above 1.6 GHz) and consequently were the first to demonstrate a possible existence of spectra with turnover at high frequencies, about 1 GHz. Kijak et al. (2011a) provided a definite evidence for a new type of pulsar radio spectra. These spectra show the maximum flux above 1 GHz, while at higher frequencies the spectra look like a typical pulsar spectrum. At lower frequencies (below 1 GHz), the observed flux decreases, showing a positive spectral index (Kijak et al. 2011a). They called these objects the gigahertz-peaked spectra (GPS) pulsars. A frequency at which such a spectrum shows the maximum flux was called the peak frequency. Kijak et al. (2011a) also indicated that the GPS pulsars are relatively young objects, and they usually adjoin such interesting environments as HII regions or compact pulsar wind nebulae. Additionally, some of them seem to be coincident with the known but sometimes unidentified X-ray sources from third EGRET Catalogue or HESS observations. We can assume that the GPS appearance owes to the environmental conditions around the neutron stars rather than to the radio emission mechanism.
2. PSR B1259-63 spectrum evolution

PSR B1259-63 was also listed by Lorimer et al. (1995) as a pulsar with positive spectral index. Therefore, it seems a natural candidate to be classified as the GPS pulsar. This pulsar is in an unique binary with a massive main-sequence Be star. PSR B1259-63 has a short period of 48 ms and a characteristic age of 330 kyr. Its average dispersion measure (DM) is about 147 pc cm\(^{-3}\) and the corresponding distance is about 2.75 kpc. The companion star LS 2883 is a 10-mag massive Be star with a mass of about 10M\(_\odot\) and a radius of 6R\(_\odot\). Be stars are generally believed to have a hot tenuous polar wind and a cooler high-density equatorial disc. The PSR B1259-63/LS 2883 emits unpulsed non-thermal emission over a wide range of frequencies ranging between radio and \(\gamma\) -rays, and its flux varies with orbital phase. We studied the radio spectrum of B1259-63 (Kijak et al. 2011b).

![Figure 1. The fits to the B1259-63 spectra for each orbital phase range (Kijak et al. 2011b), from 60 d prior to periastron (left panel) up to 186 d after it (right panel).](image)

We analysed the available measurements of the pulsed flux obtained during three periastron passages (1997, 2000 and 2004). Our analysis showed that this pulsar undergoes a spectrum evolution due to orbital motion (see Fig.1). We suggested that this effect is caused by the interaction of the radio waves with the Be star environment. While the eclipse itself can be naturally explained by free-free absorption in the stellar disc, the disc alone is not enough to explain the spectra evolution. In addition, we have shown that the peak frequency also depends on the orbital phase and therefore it varies with the changes of the pulsar environment. We argued that such behaviour can be explained by the radio-wave absorption in the magnetic field associated with the disc. We proposed a qualitative model which explains this evolution. We argued that the observed variation of the spectra is caused by a combination of two effects: the free-free absorption in the stellar wind and the cyclotron resonance in the magnetic field. This field is associated with the disc and is infused by the relativistic particles of the pulsar wind.

**B1259-63 as key factor to explain the GPS phenomenon.** Having noticed the apparent resemblance between the B1259-63 spectrum and the GPS, we suggested that the same mechanisms should be responsible for both cases (Kijak et al. 2011b). Thus, we can conclude that the GPS feature should be caused by some external factors rather than by the emission mechanism. On the other hand, the GPS pulsars are isolated radio pulsars and therefore, we cannot draw a direct analogy between the PSR B1259-63/LS 2883 system and the GPS pulsars, as the latter have no companion stars and/or discs. But the GPS pulsars apparently are surrounded by some kind of environment that can affect the spectra of those pulsars in the same way as the stellar wind.
affects the B1259-63 spectrum. All GPS pulsars have relatively high DMs that, in some cases, are too large to be accounted for by the Galactic electron density, and thus, we can speculate that there is a quite high particle density in the vicinity of these pulsars (see also Kijak et al. 2011a). Thus, we believe that this binary system can hold the clue to the understanding of gigahertz-peaked spectra of isolated pulsars. The only difference could be an invariable shape of the GPS.

3. PSR B1259-63 spectrum evolution: detailed study

Using the same database (Johnston et al. 1999, Connors et al. 2002, Johnston et al. 2005) we constructed spectra for chosen observing days. We analysed the shapes of the B1259-63 spectrum at various orbital phase ranges as it was done previously (Kijak et al. 2011b) and obtained results are consistent with those for intervals. The flux at the given frequency apparently changes with orbital phases. When the pulsar is close to periastron, the flux generally decreases at all observed frequencies and the most drastic decrease is observed at the lowest frequency. Moreover, we noticed all types of radio pulsar spectra.

PSR B1259-63 is a object with relatively high dispersion measure which means that its transition frequency is very high. This implies that we definitely have to take into consideration both refractive (RISS) and diffractive (DISS) scintillations when analysing spectra for a given day. We used diffractive bandwidth $\Delta f_{\text{DISS}}$ and timescale $\Delta t_{\text{DISS}}$. 

![Figure 2. The fits to the B1259-63 spectra for chosen days. Each panel shows different type of spectra.](image-url)
from scintillation observations of the pulsar made far from periastron at 4.8 GHz and 8.4 GHz (McClure-Griffiths et al. 1998) to estimate values of these parameters at 1.4 GHz and 2.4 GHz assuming $\Delta t_{\text{DISS}} \propto f^{1.2}d^{-0.6}$, where $f$ and $d$ denote frequency and distance respectively. We estimated the values of $\Delta t_{\text{DISS}}$ to be ranging from 40 s at 1.4 GHz to 360 s at 8.4 GHz which suggests that diffractive scintillations should not affect the average flux measurements (observing sessions was usually 4 hours long). Roughly estimated refractive timescales vary from 12 hours at 8.4 GHz to more than 20 days at 1.4 GHz. However, for lower frequencies the modulation index is relatively small which means lower uncertainty estimates when measuring flux. High frequency observations will be affected by refractive scintillations what leads to conclusion that flux values should be averaged over epochs and/or orbital phase intervals to be more reliable.

4. Conclusions

Close to the periastron point the spectra of B1259-63 resemble those of the GPS pulsars. The spectrum for the orbital epochs further from the periastron point are more consistent with typical pulsar spectra (i.e. power-law and broken). Moreover, detailed study of PSR B1259-63 spectra revealed the appearance of all types of spectral shapes, including a flat spectrum (see Fig. 2).

We believe that the case of B1259-63 can be treated as a key factor to our understanding of not only the GPS phenomenon (observed for the solitary pulsars with interesting environments) but also other types of untypical spectra as well (e.g. flat or broken spectra). This in turn would suggest, that the appearance of various non-standard spectra shapes in the general population of pulsars can be caused by peculiar environmental conditions.

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References

Pulsar emission at the bottom end of the electromagnetic spectrum

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Abstract. Pulsars are arguably the only astrophysical sources whose emission spans the entire electromagnetic spectrum, from decameter radio wavelengths to TeV energies. The LOw Frequency ARray (LOFAR) offers the unique possibility to study pulsars over a huge fractional bandwidth in the bottom 4 octaves of the radio window, from 15–240 MHz. Here we present a LOFAR study of pulsar single pulses, focusing specifically on the bright nearby pulsar B0809+74. We show that the spectral width of bright low-frequency pulses can be as narrow as 1 MHz and scales with increasing frequency as $\Delta f/f_c \sim 0.15$, at least in the case of the PSR B0809+74. This appears to be intrinsic to the pulsar, as opposed to being due to propagation effects. If so, this behavior is consistent with predictions by the strong plasma turbulence model of pulsar radio emission. We also present other observed properties of the single pulses and discuss their relation to other single-pulse phenomena like giant pulses.

Keywords. radiation mechanisms: nonthermal, methods: data analysis, pulsars: individual (PSR B0809+74)

1. Introduction

In recent years a number of studies of strong individual pulses from bright nearby pulsars were performed, including some at low radio frequencies (see, e.g., Kuzmin 2006 and references therein; Weltevrede et al. 2006; Karuppusamy et al. 2011). Higher radio frequencies are more favorable for pulsar studies because of several factors, such as inter-channel dispersion, scattering, the Galactic synchrotron background, and the ionosphere. Nonetheless, the very low-frequency range is interesting for pulsar studies because of pulse-profile evolution, which can become quite dramatic towards the lowest frequencies (Hassall et al. 2012). Next, some phenomena are potentially not seen at higher frequencies (or become less pronounced there), in particular the anomalously bright individual pulses from five nearby pulsars including PSR B0809+74, reported by Ulyanov et al. (2006) based on observations with the UTR-2 radio telescope. It is not clear whether these pulses are attributed to giant pulses or other single-pulse phenomena observed from other pulsars at higher frequencies. In these proceedings we report the first broadband low-frequency single-pulse study of the PSR B0809+74 using the LOFAR telescope.

2. Observations and Data processing

Observations were carried out using the Low Band Antennas (LBAs) in the LBA OUTER array mode, where the 48 outermost dipoles in each LBA field are used. The instantaneous bandwidth of 46.875 MHz centered at a frequency of about 38 MHz was split into 240 subbands of 32 channels each and originally sampled every 491.52 $\mu$s. Each observation was the coherent sum of the six “Superterp” stations, CS002–CS007. A detailed
Figure 1. Examples of characteristic spectra and profiles of individual pulses of the pulsars B0809+74. The number in the top-right of each panel shows the pulse number from the beginning of the observation. There are 438 bins in the period, and each spectrum is comprised of 480 channels of 97.656 kHz each.

description of LOFAR’s pulsar observing modes and the online data reduction pipeline is given in Stappers et al. (2011).

The data were converted from the LOFAR beam-formed format to the PSRFITS data format, corrected for the varying gain over the LBA band, and processed with DSPSR† (van Straten & Bailes 2011) to form both an integrated profile as well as single-pulse integrations. We used pdmp from PSRCHIVE‡ (Hotan et al. 2004) on a sample of strong pulses to determine the best DM for the time of our observations: 5.752 pc cm$^{-3}$, with the DM jitter between the pulses being on the order of 0.002 pc cm$^{-3}$. Many of the pulses showed very narrow-band structure in their spectra (see Figure 1, and details below). Using a 2D time-frequency search technique (Kondratiev et al., in prep) we next analysed the spectra of the complete sample of single pulses.

3. Results

The complete results of our study will be presented in Kondratiev et al. (in prep); here we briefly present a few highlights.

Figure 1 shows some typical pulses from the PSR B0809+74. In a given pulse, emission can occur in either the leading or trailing component; in both components at the same time; or sometimes even in three components corresponding to three subpulse-drift bands (see, e.g., pulse #941 on Figure 1). The frequency structure of the pulse spectra can be also quite different. For instance, pulse #941 shows a very narrow emission patch at 19 MHz in the second component, but the strongest emission from other two components occurs at the higher frequencies. Other examples (e.g. pulse #2003) show very broadband structure comprised of a number of smaller, individual patches with the maximum tending to be at lower frequencies (<30 MHz). On average the pulse spectra of the PSR B0809+74 are quite narrow and constitute only half of the band.

Figure 2 presents the pulse energy distribution for the pulsar B0809+74. The energy is calculated for the emission patches of every pulse component in the profile rather than in the entire band due to the presence of narrow-band pulses. Distributions are skewed towards higher energies due to the search technique as we searched for highest spectral flux density. It is clear that distributions are very similar at low energies with slightly less number of low-energy patches in the ON-pulse window. A few positive outliers for the OFF-pulse histogram indicates the presence of RFI but their number is insignificant.

† http://dpsr.sourceforge.net
‡ http://psrchive.sourceforge.net
Figure 2. Pulse energy distribution for B0809+74. Energies are for the emission patches over patch’s frequency width normalized by the energy of the average profile over the entire band. Distributions in green and yellow are for ON-pulse and OFF-pulse phase windows, respectively, using the same search technique with the threshold of 1\(\sigma\). The distributions in light blue are for the strong patches with the spectral flux density over 5\(\sigma\). We also show the ON-pulse histogram for the strong patches with the spectral peak flux density \(>5\sigma\). The roll-off of the histogram at low energies represents the selection bias for patches with peak spectral fluxes close to the detection threshold. The apparent larger fraction of stronger patches than 1\(\sigma\)-patches for the same energy, is caused by the fact that overall number of found patches is much larger for the 1\(\sigma\) than the 5\(\sigma\) threshold.

We fit a normal, log-normal and power-law distribution with low-energy cutoff. For our fits we excluded the very high energy tail of the distributions that have small statistics. The lognormal distribution provides the best goodness of fit. However, fitting the power-law distribution to the high-energy tail for energies \(>2.4\langle E\rangle\) provides better results. In general, the significance of the fit is not high enough for both pulsars to reject neither lognormal nor power-law distributions, and the better statistics is needed.

The narrow-band emission of the PSR B0809+74

The narrow-band spectra of some of the pulses from the PSR B0809+74 are quite unique and have never been observed at higher frequencies. We found it very unlikely that this narrow-band frequency pattern is caused by either ISM scintillations or ionosphere. For the former estimates of the decorrelation bandwidth give values of \(\lesssim 2\) kHz, so all scintillations should be completely averaged out in our data. For the ionosphere the rate of change in its state is long (mins–hours) compared to time scales of about a second for the use case when narrow-band pulses follow each other.

Figure 3 shows the dependence of the patch’s frequency width on their central frequency for the pulsar B0809+74 for the strong patches with the energy \(E > 2\langle E\rangle\). Though data points are somewhat scattered, they qualitatively lie on the line, \(\Delta f/f_c \sim 0.15\). This agrees very well with the prediction from the strong plasma turbulence (SPT) model (Weatherall 1998). The SPT model of pulsar radio emission predicts narrow-band radiation with \(\Delta f/f \sim 0.1 – 0.2\). If indeed true, this would also provide a direct link between giant pulses and anomalously intensive pulses observed at low frequencies.
4. Summary

We observe occasional bright narrow-band pulses from the PSR B0809+74 at 15–62 MHz. Their spectra can be as narrow as 1 MHz and tend to have a width of 3 MHz.

We identified pulse sequences from the pulsar B0809+74 where narrow patch of emission is drifting up in frequency from pulse to pulse. We see evidence for similar frequency drift for at least one other pulsar.

The origin of these narrow-band pulses is likely to be pulsar-intrinsic rather than due to propagation effects in ISM or ionosphere.

At the moment, the observed pulse properties of the PSR B0809+74 do not allow us to relate low-frequency bright narrow-band pulses to “spiky emission”, or to either giant pulses or regular emission.

For PSR B0809+74, the spectral width of the strong emission patches scales with increasing frequency as $\Delta f/f_c \sim 0.15$, qualitatively agreeing with the prediction of the SPT model. This supports the relation between bright narrow-band pulses at low frequencies and giant pulses.

Acknowledgements

LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy.

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"An X-Raydio Switcheroo" –
The detection of correlated mode changes in radio and X-ray

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Abstract. We present high-sensitivity XMM/LOFAR observations that show for the first time that mode switching extends from radio to X-ray. In pulsar B0943+10, the known changes in radio profile and drift rate are confidently tied to simultaneous changes in X-ray emission.

In mode switching, seen in many pulsars, profile and subpulse-drift behavior change almost instantaneously. The mechanism for these drastic changes, or for the bi-stable emission behavior, is not understood; while even for the basic emission mechanism different families of theories (e.g. vacuum gap, or space-charge limited flow models) exist.

To discriminate between such models, we carried out a campaign of 42 hours of simultaneous LOFAR/XMM-Newton observations on PSR B0943+10. Through LOFAR’s unparalleled low-frequency sensitivity, mode changes were pinpointed to 10-second accuracy. XMM X-ray photons were next separated by the two radio modes. We discovered large modal differences in the X-ray pulsations, flux, and spectral shapes: in the radio-bright mode, no X-ray pulsations are detected – but in the radio-quiet mode, B0943+10 is strongly pulsating in X-ray.
A multi-wavelength campaign to study giant pulses from the Crab Pulsar

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Abstract. We are currently undertaking a monitoring campaign with NASA 70-m antennas to capture a large sample of Crab Giant Pulses (CGP) at multiple radio wavelengths. The goal of this campaign is to carry out a correlation study of CGPs at radio frequencies with pulsed emission from the Crab pulsar with Fermi photons at X-ray. After a year of this study, we expect around 200 Fermi photons to coincide with a CGP radio-frequency detection, allowing us to either confirm a predicted correlation in average gamma-ray pulsed flux increase with GP emission, or place a tight upper limit, at least a factor of 10 more constraining than previous work. We will report on the status of this campaign and will present our preliminary results and prospects for future improvements in receivers and back-end instrumentation.
Session 13

Future facilities
The Five-hundred-meter Aperture Spherical radio Telescope project and its early science opportunities

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Abstract. The National Astronomical Observatories, Chinese Academy of Science (NAOC), has started building the largest antenna in the world. Known as FAST, the Five-hundred-meter Aperture Spherical radio Telescope is a Chinese mega-science project funded by the National Development and Reform Commission (NDRC). FAST also represents part of Chinese contribution to the international efforts to build the square kilometer array (SKA). Upon its finishing around September of 2016, FAST will be the most sensitive single-dish radio telescope in the low frequency radio bands between 70 MHz and 3 GHz. The design specifications of FAST, its expected capabilities, and its main scientific aspirations were described in an overview paper by Nan et al. (2011). In this paper, we briefly review the design and the key science goals of FAST, speculate the likely limitations at the initial stages of FAST operation, and discuss the opportunities for astronomical discoveries in the so-called early science phase.

Keywords. ISM: atoms, ISM: clouds, Galaxy: evolution, masers, gravitational waves, techniques: spectroscopic, surveys

1. The FAST Project

FAST is an Arecibo-type antenna with three outstanding aspects. First, it is sited in a deep karst depression, Dawodang in Guizhou province in southwestern China, which allows for a 500 meter spherical aperture and a zenith angle of 40 degrees. Second, the spherical aberration is to be corrected by an active primary surface comprised of more than 4000 steerable panels. Third, a light-weight feed cabin will be driven by six cables and a servomechanism plus a parallel robot to realize close-loop precision control. Compared with Arecibo, these features facilitate three main advantages, about twice the effective collecting area, about twice the sky coverage, and a much lighter focal cabin structure and thus a cleaner optical path. An original image of the site, the schematics of FAST optics, and a 3D model are shown in Figure 1.

The high frequency limit of FAST is determined by the size of the panels. The depth of the karst depression along with the design of the suspension structure determines the opening angle of FAST. The current surface segmentation plan and overall constraints of budget and project time are shown to be sufficient to realize the high frequency limit of 3 GHz and a zenith angle 40\degree. The raw sensitivity in L-band, which is the core band for most significant sciences of FAST, reaches 2000 m\textsuperscript{2} K\textsuperscript{-1}, thanks to the huge collecting area and up-to-date receiving system. A 19-beam feed horn receiver array is planned for L-band to increase the survey speed. Maximum slewing time is around 10 minutes,
Table 1. Main technical specifications of FAST.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical reflector: Radius</td>
<td>300m</td>
</tr>
<tr>
<td>Aperture</td>
<td>500m</td>
</tr>
<tr>
<td>Illuminated aperture: D_{ill}</td>
<td>300m</td>
</tr>
<tr>
<td>Focal ratio: f/D</td>
<td>0.4611</td>
</tr>
<tr>
<td>Sky coverage: zenith angle</td>
<td>40</td>
</tr>
<tr>
<td>Frequency: 70MHz - 3GHz</td>
<td></td>
</tr>
<tr>
<td>Sensitivity (L-Band): A/T</td>
<td>~2000</td>
</tr>
<tr>
<td>System temperature T_{sys}</td>
<td>~20K</td>
</tr>
<tr>
<td>Resolution (L-Band):</td>
<td>2.9'</td>
</tr>
<tr>
<td>Multi-beam (L-Band): beam number</td>
<td>19</td>
</tr>
<tr>
<td>Slewing time:</td>
<td>&lt;10 minutes</td>
</tr>
<tr>
<td>Pointing accuracy:</td>
<td>8''</td>
</tr>
</tbody>
</table>

which is restricted by the power of high-voltage electromotor. A summary of the technical specifications of FAST (phase I) can be found in Table 1.

Figure 1. Upper Left: Partial view of the original site as seen in Nov of 2009. Upper Right: FAST optical geometry. Lower: A 3D model of FAST.
The FAST project consists of 6 subsystems (Figure 2).

1) **Site Survey and Excavation.** The natural shape of a karst formation is close to be part of a sphere. Still, about one million cube meters of earth need to be removed, which counts for a few percent of the total volume of a half sphere with a 500 m diameter. As of September 2012, the site excavation and protection of the dangerous rocks and slopes are near completion.

2) **Active Reflector.** The active main reflector, which is the most expensive part of the project, is supported by a cable network. More than 2000 actuators drive tie-down cables according to the feedback from the measuring system to deform the surface. The whole reflector consists of about 4400 triangular panels, which give a RMS error smaller than 5 mm. With a side dimension of about 11 m, the reflectors are to be made of aluminum sheet as the surface, spatial truss of aluminum as the backup and an adjustable layer in between. The RFI properties and the life time of actuators are being investigated. A final selection is expected soon between mechanical and hydraulic actuators. Cable fatigue problem poses a major challenge to the FAST design. Extensive numerical and experimental investigation have been carried out to decrease the stress.

*Figure 2.* Illustration of the 6 subsystems of FAST.
The range of the cable required. We also have developed a new type of steel strand with ultra high fatigue resistant property. The current design and chosen materials are shown to satisfy the operational need with sufficient reserve (Jiang 2011).

3) Feed Cabin Suspension System. The feed cabin of FAST is supported and driven by cables and servomechanism without any solid structure between the cabin and the towers. To control the position of the cabin to within the error budget, which is the most difficult part of the FAST design, a secondary adjustable system is employed inside the cabin. Numerous scaled models were made to verify the feasibility of the concept. The team has also carried out end-to-end simulation through a collaboration with MT Mechatronics and Technical University Darmstadt. These analysis show that the displacement of feed cabin after first adjustment control can be constrained to within a few centimeter and the secondary stabilizer further reduces the error to a few millimeters, which meets the requirement.

4) Measurement and Control System. The FAST design requires a system position accuracy of about 2 mm on a range of about 150 m, which amounts to a linear dynamic range of 5 orders of magnitude. The measurement and control of the panels and the cabin need to happen in real time. The 3D position and the orientation of the focus cabin will be sampled at a rate > 10 Hz. The profile of the main reflector will be measured through 1000 nodes in illuminated area in real time every couple of minutes. The datum lines have been established. The accuracy and stability are shown to be better than 1 mm.

5) Receiver and Backend System. FAST will be equipped with nine sets of receivers, covering a frequency range of 70MHz-3GHz. Scientific backends, time/frequency standard, and monitoring/diagnostics of the receivers are undergoing optimization. The 19 beam feed-horn array at L-band will be the core survey instrument of FAST and is under development through a trilateral collaboration among NAOC, JBCA (Jodrell Bank Centre for Astrophysics) and CSIRO (Commonwealth Scientific and Industrial Research Organisation). The L-band single pixel receiver has been developed in the FAST lab, covering 1.1 GHz to 1.9 GHz with return loss better than -22dB and isolation better than -22dB across the band.

6) Observatory. The operation center will be located in a lower depression adjacent to the FAST site. The preliminary design has been approved. We expect the main structure of the building to be made exclusively out of wood, which naturally fit into the ambiance of Guizhou.

2. Key Science Goals

The origin of the observable universe, the origin of our world with the Sun and the Earth, and the origin of intelligent life are overarching questions of natural sciences. FAST, with its unparalleled collecting area and its state of art receiver systems has a unique window for contribution through precise measurements of matter and energy in the low frequency radio bands.

The key science goals of FAST are based on observables between 70 MHz and 3 GHz, including the 21 cm HI hyperfine structure line, pulsar emission, radio continuum, recombination lines, and molecular spectral lines including masers.

The majority of the normal matter in the universe is in the form of HI gas. Compared with Arecibo, FAST will have three times the scan speed at L-band and twice the sky coverage. A key goal for Galactic ISM study will be a systematic study of very cold atomic gas through measuring HI Narrow Self-Absorption features (HINSA; Li & Goldsmith 2003), which will be analyzed together with CO surveys of comparable resolution. For the local universe, FAST will conduct blind surveys to measure the gas mass especially
in optically dark galaxies. Such census of gas will help explain the discrepancy between dark matter simulation and the observable universe, in particular, the "missing satellite problem".

Using the 19 beam L-band focal plane array, FAST aims to discover over 4000 new pulsars (Smits et al. 2009), about 300 of which should be milli-second pulsars. The followup timing studies of these fast pulsars will be a substantial addition to current pulsar timing arrays. We are looking into the quantitative impact of FAST pulsar studies upon the detectability of gravitational wave, both from the stochastic background and single events.

FAST will also perform targeted studies of radio continuum, recombination lines, and molecular lines. These studies aim to enhance our understanding of the galactic structure, ISM content, and planetary physics. For example, in terms of extra-galactic maser search, FAST is expected to detect more than 1000 OH mega-masers up to a redshift of 2 (Zhang, Li & Wang 2011). Such a FAST maser sample represent a 10 fold increase from the sum of all current known OH mega-masers. FAST also stands a good chance of detecting the most distant OH mega-masers.

We also expect to attempt direct detection of exoplanets in meter wave band. Given the large beam of FAST in its lowest frequency band, the challenge of confirming the radio signal from an exoplanet will be systematics and stellar radio emission. We have conducted preliminary studies and plan to utilize the high sensitivity of FAST in that FAST will be able to sample such emission at about 10 m interval. The quasi-periodicity of planetary radio burst is tied to the spin of the planet, which is counted in days. The time-modulation of radio signals will much enhance the detectability of exoplanet by FAST.

3. Early Science Opportunities

We consider the first 6 months to a year after first light to be the FAST “early science” phase, during which a few hands-on projects will try to utilize the sensitivity of FAST before the complete suite of receivers and observing modes are successfully implemented.

The complexity and the innovative nature of the FAST systems pose many challenges. The main foreseeable one is the real-time control. With a total error budget of 2 mm, the FAST systems, including the main active reflectors and the receiver cabin, have to be constrained precisely through a closed feedback loop. The difficulty of realizing such precise control loop goes up substantially with frequency. Therefore, there exist great motivation in the early science phase to carry out projects in wavelengths longer than the L-band. In terms of observing modes, those involving complex scan patterns and fast driving/switching should be avoided.

These two considerations discussed above mean that the early science programs should target point sources with strong signatures below 1 GHz. Spectroscopic lines from the Orion nebular clearly satisfy such requirements. Our plan is to perform deep spectroscopic scan in bands as wide as possible in low frequency ranges. There are \( \lambda \) doubling line of CH, possible CH\(_3\)OH maser, recombination lines, and numerous other lines of more complex species in frequencies lower than 1 GHz. With a comprehensive Orion source model expected from Herschel studies, such a spectral line survey also holds the potential for discovering new lines.

We have carried out a numerical experiment to identify the optimum frequency for FAST pulsar search in a drift scan mode. Based on an updated version of the pulsar population model by Lorimer et al. (2006), our simulations fit the detection rate of the Parkes Multibeam Survey, Parkes 70 MHz survey, and the GBT survey simultaneously.
by altering the spectral index and deviation of spectra index distribution together. Our
results show that the maximum detection rate for a drift-scan pulsar search by FAST
can be achieved around 500 MHz, with a relatively flat ‘plateau’ between about 400 MHz
and 700 MHz. Pulsar searches, especially toward M31, in that frequency range will thus
be of high priority as a FAST early science program.

In the early science phase, FAST should be able to detect compact radio continuum
sources, such as the Gigahertz Peaked-Spectrum (GPS) sources. FAST will enlarge the
sample to fainter flux end and shed lights into the origin of emission from these sources.

Given the technical constraints and scientific considerations regarding FAST early
science operation, two additional receivers are being studied specifically for this phase.
One is a 7-beam feed horn array operating between 400 MHz and 560 MHz and the
other one is a single pixel receiver covering 270 MHz to 1450 MHz. The multi-beam
system is being optimized for conducting pulsar searches in drift mode. The wide-band
receiver is designed primarily for line surveys. These two systems are much cheaper and
lighter compared with the suite of receivers in the formal design for normal operation. We
expect them to come online first and provide a platform for exploring the discovery space
of FAST as soon as possible. Within the technical constraints of early science operations,
there will still be ample opportunities for focused programs of significant impact. Careful
consideration of low frequency sources, existing surveys, and feasibility are required for
early science programs of FAST.

The FAST group value international collaboration immensely, both in terms of hard-
ware design and of scientific planning and research. We expect to formulate key programs
well in advance of the first light of FAST, expected in September of 2016. The detailed
policies and the arrangements of the call for proposals will be formulated by an interna-
tional advisory committee, which will report to and be approved by Chinese Academy of
Sciences. These key programs are expected to be mainly lead by Chinese PIs and with
substantial international collaboration, which should be given advantages in the review
process.

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References
NuSTAR observations of rotation-powered pulsars and magnetars

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Abstract. NASA’s NuSTAR observatory is the first focusing hard X-ray telescope. Launched in June 2012, NuSTAR is sensitive in the 3–79 keV range with unprecedented $\sim17''$ FWHM angular resolution above 12 keV, a result of its multilayer-coated optics and 10-m focal length. With its large effective area (900 cm$^2$ at 10 keV), NuSTAR has point-source sensitivity $\sim$100 times better than previous hard X-ray telescopes. Here we describe NuSTAR and its planned work on rotation-powered pulsars and magnetars during its nominal 2-yr baseline mission that has just commenced.

Keywords. stars: neutron, pulsars: general, X-rays: general, X-rays: binaries, telescopes

1. Introduction

The hard X-ray regime is one of the few underexplored areas of the electromagnetic spectrum in astrophysics, yet has great scientific significance. In contrast to X-rays with energies below $\sim$3 keV, hard X-rays are largely unaffected by photoelectric absorption, either due to material intervening in the Galaxy or intrinsic to the source. Thus hard X-rays permit unobscured views to distant Galactic Plane sources, as well as to the hearts of otherwise highly obscured targets. Moreover, hard X-ray studies probe non-thermal emission regimes above where thermal X-rays confuse spectra, allowing probes of powerful particle acceleration mechanisms. Several radioactive decay lines, such as the 68-keV line of $^{44}$Ti, lie in the hard X-ray range, and offer unique probes of short-lived phenomena such as supernovae.

Although of great astrophysical value, hard X-rays have been notoriously hard to focus. Previous hard X-ray telescopes such as the IBIS instrument aboard INTEGRAL
used coded-mask technologies in which a specially patterned coded aperture mask casts a ‘shadow pattern’ on an X-ray detector. Deconvolution of the shadow pattern typically yielded point-spread-functions on the order of 12′ in the hard X-ray regime, not highly competitive with most other areas of astronomy. By contrast, *NuSTAR*’s mirrors, arranged in a conical approximation to a standard Wolter-I type geometry, make use of newly developed depth-graded multilayer coatings that effectively Bragg-reflect incoming X-rays in the 3–79 keV range with high grazing angles. To beef up collecting area, *NuSTAR* uses many nested co-axial mirrors, each specially coated and shaped. The high-energy range of the X-rays demands a 10-m focal length, with the collected X-rays focused on CdZnTe detectors. *NuSTAR* has two independent mirror and detector modules, with the former separated from the latter by a 10-m-long mast. These detectors have spectral resolution of 0.9 keV at 60 keV, and yield time resolution of 100 µs. The resulting mirror/detector combination yields a field of view of 13′ × 13′, and a FWHM point-spread-function of ∼17″. *NuSTAR* has a Target-of-Opportunity response time of < 48 hr. See Harrison et al. (2010) for more details of the *NuSTAR* mission. Figure 1 shows an artist’s concept of *NuSTAR* deployed in space, and Figure 2 shows *NuSTAR*’s first light observation of Cyg X-1, and the contrast of the PSF with that of the previous state-of-the-art hard X-ray instrument aboard INTEGRAL. In Figure 3 we show *NuSTAR*’s two-telescope effective area curve, along with those of two other focusing X-ray telescopes for comparison. Table 1 summarizes *NuSTAR*’s sensitivity in comparison with other previous hard X-ray telescopes.

*NuSTAR*’s 10-m mast deployed not long after the mission’s flawless June 13, 2012 Pegasus launch from the Reagan Test Site on Kwajalein Atoll in the Pacific Ocean. *NuSTAR* now sits in a 600 km × 620 km orbit at 6° inclination. This orbit results in an estimated 10-yr lifetime for *NuSTAR*, which has no consumables. Presently *NuSTAR* is funded only for a Principle-Investigator-led baseline 2-yr mission; however, extension beyond this baseline mission and the possibility of a Guest Investigator program are currently under discussion. Following *NuSTAR*’s calibration phase, all data obtained

### Table 1. *NuSTAR*’s sensitivity in comparison with other hard X-ray instruments.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTEGRAL</td>
<td>~0.5 mCrab (20-100 keV) with &gt;Ms exposure</td>
</tr>
<tr>
<td>Swift (BAT)</td>
<td>~0.8 mCrab (15-150 keV) with &gt;Ms exposure</td>
</tr>
<tr>
<td>NuSTAR</td>
<td>~0.8 µCrab (10-40 keV) with 1 Ms exposure</td>
</tr>
</tbody>
</table>
during the nominal 2-yr mission will be publicly available via HEASARC following a brief verification period.

2. Current status of NuSTAR

As of August 1, 2012, NuSTAR has completed its calibration phase and started its science operations phase. Thus far, no major anomalies have been identified. The in-orbit mast motion is consistent with pre-orbit predictions. The spectral resolution is better than the pre-orbit specified requirement. The background appears to be stable and within the pre-launch requirements. The low-energy (3–20 keV) calibration agrees with that of Swift XRT at the < 3% level. The high-energy calibration is presently under study but thus far there are no major surprises. Timing calibration is also underway; with post-facto clock-drift corrections, absolute timing at the few-ms level is expected, although for fixed pointings and short observations, the full 100-μs resolution will be usable.

3. NuSTAR science Working Groups

Science to be done with NuSTAR has been organized into multiple Working Groups. These are, with Working Group Chair in parentheses:

- Heliophysics and Protostar Flares (D. Smith)
- Galactic Plane Survey (C. Hailey)
- Supernovae (S. Boggs)
- Supernova Remnants and Pulsar Wind Nebulae (F. Harrison)
- Galactic Accreting Binaries (J. Tomsick)
- Magnetars and Rotation-Powered Pulsars (V. Kaspi)
- Ultraluminous X-ray Sources (F. Harrison)
- Extragalactic Surveys (D. Stern)
- Blazars and Radio Galaxies (G. Madejski)
Figure 3. Effective area as a function of energy for the combination of NuSTAR’s two telescopes, compared with two other focusing X-ray missions.

- AGN Physics (G. Matt)
- Obscured AGN (D. Stern)
- Galaxy Clusters (A. Hornstrup, S. Molendi)
- Starburst and Local Group Galaxies (A. Hornschemeier)

A list of the membership of each of these working groups is provided at http://www.nustar.caltech.edu/for-astronomers/science-working-groups.

4. NuSTAR Working Group on rotation-powered pulsars and magnetars

NuSTAR’s Working Group on rotation-powered pulsars and magnetars has been allocated 1.2 Ms of Priority A observing time during the nominal 2-yr mission. After careful consideration of NuSTAR’s unique strengths as well as the most interesting tractable problems relevant to high-energy X-rays for rotation-powered pulsars and magnetars, our Working Group decided on the Priority A target list described below (and also available at the above-mentioned web site).

Note that the Working Group chose heavy weighting toward magnetars. This is because of the surprising high-energy turnover in their X-ray spectra as discovered by INTEGRAL and RXTE (Kuiper et al. 2006). Indeed some magnetars have more energy output above 10 keV than below it! This emission is both unpredicted and not understood, though some models have been suggested (e.g. Heyl & Hernquist 2005; Baring & Harding 2007; Beloborodov & Thompson 2007; Beloborodov 2012) and some intriguing correlations noted (Kaspi & Boydstun 2010; Enoto et al. 2011). By contrast, many of the most energetic, hence X-ray luminous rotation-powered pulsars show simple power-law spectra from low through high X-ray energies.
• **Magnetar Target-of-Opportunity (150 ks):** *NuSTAR* plans to observe a magnetar outburst and relaxation following a burst and/or flux trigger, provided likely by either *Swift/BAT* or *Fermi/GBM*. The goal here is to monitor simultaneously the outburst and relaxation behavior of the soft and hard X-ray components, to see whether they vary in concert both spectrally and in terms of flux. This will help constrain models for the origin of the hard component and how it is related to the observed thermal component.

• **1E 2259+586 (170 ks):** This magnetar was only marginally detected in the hard X-ray band by RXTE and INTEGRAL, owing to its soft spectrum below 10 keV and in spite of its extremely hard spectrum above (Kuiper et al. 2006). Indeed only the pulsed component was measurable with those instruments. *NuSTAR* will provide the first high quality broad-band X-ray spectrum for this target, which has the most extreme spectral turnover yet seen in any magnetar.

• **1E 1048−5937 (400 ks):** This is the lone ‘classical’ regularly monitored magnetar for which no hard X-ray emission has yet been detectable. Assuming a spectral turnover in agreement with the rough correlation suggested by Kaspi & Boydstun (2010), *NuSTAR* should provide the first broadband spectrum for the source, and hence a clear test of the putative correlation.

• **AE Aquarii (126 ks):** This target is an intermediate polar, i.e. an accreting white dwarf that has shown unique signatures of possible non-thermal X-ray emission in *Suzaku* observations (Terada et al. 2008). Specifically a putative sharp spike in its light curve was reported and is reminiscent of non-thermal X-ray pulses seen in rotation-powered pulsars. This is suggestive of the intriguing possibility that magnetospheric particle acceleration in this white dwarf is occurring just like that seen in rotation-powered pulsars. *NuSTAR’s* superior point-source sensitivity will allow us to clearly test *Suzaku’s* report. *NuSTAR* observed AE Aquarii in September 2012. These data are currently being analyzed.

• **Geminga (260 ks):** Geminga is among the very brightest gamma-ray sources known (Abdo et al. 2010) yet shows relatively faint, mainly thermal X-ray emission (e.g. Karlglaztev et al. 2005). An archetype for many other such X-ray faint/gamma-ray bright rotation-powered pulsars, *NuSTAR* observations can help constrain the energy at which the spectrum turns up, and whether the faint power-law emission seen at the high end of the soft X-ray band extrapolates up to the *Fermi* band. *NuSTAR* observations of Geminga were done in September 2012 and are currently under analysis. Another carefully considered target for this observation was the Vela pulsar. However, its bright and very large pulsar wind nebula yields too high a background for the pulsar to be usefully studied with *NuSTAR*.

• **PSR J1023+0038 (100 ks):** This rotation-powered pulsar is a millisecond pulsar in a 0.2-day orbit with a non-degenerate companion star that apparently had an accretion disk in the past decade (Archibald et al. 2009). X-ray emission from the system as observed with *XMM* and *Chandra* (Archibald et al. 2010; Bogdanov et al. 2011) shows a hard power-law tail suggesting detectability well above 10 keV with *NuSTAR*. This system is a unique transition object between the millisecond pulsar and low-mass X-ray binary phases of binary evolution. As such, it can further serve as a comparison via *NuSTAR*-observed spectral and timing behavior with current quiescent low-mass X-ray binaries that show similar hard X-ray power laws. The latter have been hypothesized to indicate the presence of unseen millisecond radio pulsars which become active when the X-ray binary is in its quiescent state (e.g. Burderi et al. 2003).
• 1E 1841−045 (45 ks): This target is a magnetar located at the center of the supernova remnant Kes 73. It was among the first magnetars noted by Kuiper et al. (2006) to be a hard X-ray emitter. NuSTAR, with a relatively short exposure, can measure an exquisitely precise spectrum, clearly defining the turnover region as well as the pulsed fraction as a function of energy. This target’s emission will also serve as a sanity check for comparison with previous measurements, and coupled with other such comparison observations using other objects, can check for variability in this source.

5. Conclusions

NuSTAR's superb capabilities and flawless launch made this an exciting time in high-energy astrophysics. The telescope is poised to tackle a wide range of astrophysics with revolutionary angular and spectral resolution in its energy range. For rotation-powered pulsars and magnetars, NuSTAR will be observing some of the most interesting objects known, and tackling problems that have great relevance to a wide class of astrophysical sources in high-energy astrophysics. Please stay tuned for these upcoming science results, which should be forthcoming in early 2013, once NuSTAR’s basic calibration is complete and these unprecedented data sets are analyzed.

References
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Terada, Y. et al. 2008, PASJ, 60, 387
The Square Kilometre Array

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Abstract. The Square Kilometre Array (SKA) is a global project to design and construct the
next-generation international radio telescope operating at metre to cm wavelengths. The SKA
will be an interferometric array with a collecting area of up to one million square metres and
maximum baseline of at least 3000 km, and is designed to address fundamental questions in
cosmology, physics and astronomy. The key science goals range from the epoch of re-ionization,
dark energy, the formation and evolution of galaxies and large-scale structure, the origin and
evolution of cosmic magnetism, strong-field tests of gravity and detection of gravity waves.

The SKA project is now entering a final design for an SKA Observatory to begin to be built in
the latter half of this decade that will include facilities in South Africa and Western Australia.
The SKA design relies on advances in several technologies that will be prototyped over the
next few years, and demonstrated for astronomical observations on SKA precursor telescopes.
Scientific operations of the first 10% scale phase of the SKA is targeted for 2020.

Keywords. instrumentation: interferometers, techniques: interferometric, radio continuum: gen-
eral

1. Introduction

The Square Kilometre Array (SKA) is a next-generation radio telescope for the metre
to centimetre wavelength regime. The SKA conceptual design was developed by a con-
sortium of institutions in 22 countries, including Argentina, Australia, Brazil, Canada,
China, France, Germany, India, Italy, The Netherlands, New Zealand, Poland, Portugal,
Russia, South Africa, Sweden, United Kingdom and the United States. The project is now
entering the detailed design phase with participation at time of writing of 10 countries,
with a target to begin construction of the first phase of the telescope around 2016.

The SKA will be an interferometric array with a collecting area of order one million
square metres, providing a sensitivity about 50 times higher than the largest currently
existing radio telescopes. Taking advantage of technology developments in radio frequency
devices and digital processing it will achieve a sky imaging capacity 10,000 times faster
than our current best imaging radio telescopes. The science case for the SKA has been
under development for over a decade, e.g. Taylor (1999), Carilli & Rawlings (2004). The
major leap in our ability to observe the universe enabled by the SKA will advance a
broad range of modern astrophysics. The SKA science community has identified five key
science areas where the SKA is targeted to make transformational advances in questions
of fundamental importance in physics and astrophysics.

- Strong-field tests of gravity using pulsars and black holes: Surveys will detect tens
  of thousands of new pulsars including binary systems, some potentially with black hole
  companions. The sensitivity of the SKA will allow ultra-precise timing of pulsar signals.
  Thousands of millisecond pulsars will be detected; the most stable will form a pulsar
  timing array for detection and study of gravitational waves.
The origin and evolution of cosmic magnetism. Surveys of polarization properties of the sky will yield measures of polarized synchrotron radiation arising from relativistic particles interacting with magnetic fields. Faraday Rotation Measure synthesis will be possible for more than $10^8$ polarized extragalactic radio sources out to cosmological distances, allowing the evolution of magnetic fields in galaxies to be traced over cosmic time, and providing a sensitive probe of the magnetic cosmic web that may be associated with the formation of large-scale structure.

- Probing the Dark Ages: At its lowest frequencies the SKA will probe the structure of the neutral universe during the "dark ages" before the first "objects" were formed, as well as the subsequent epoch of reionization.

- Galaxy evolution and cosmology. Atomic hydrogen emission will be detectable in normal galaxies to high redshift, providing measure of the cosmic evolution of HI and star formation. Radio continuum tracing star formation will be detectable to arbitrary redshift and the wide-field of view capability will trace out the large scale distribution of galaxies to high $z$, allowing precise studies and determination of the equation of state of dark energy.

- The conditions for and existence of life elsewhere in the Universe: Sub-AU imaging of thermal emission will trace the process of terrestrial planet formation and probe the dense proto-planetary environments for pre-biotic molecules that are the building blocks of life. The raw sensitivity and field of view of the SKA will allow leakage radiation to be detected from potential civilizations in planetary systems around millions of solar type stars.

Complete and current information about the SKA can be found at the project web site http://www.skatelescope.org, and a detailed description of the SKA can be found in Schilizzi et al. (2010).

2. The Square Kilometre Array

2.1. SKA technology and timeline

The timeline for the SKA project is shown in Table 1. The SKA project completed a conceptual design effort in 2011 with contributions from over 60 institutes in 20 countries. Achieving a design of the scale and scope of the SKA telescope has relied on advances in the costs and capabilities of a range of technologies, including:

- high performance, low-cost reflector antennas
- wide-field of view focal and aperture plane array receiver systems,
- broad-bandwidth receivers and digital transport and processing devices

Application of many of these technologies for astronomy will be demonstrated over the next few years. For example, focal-plane phased-array receiver systems and composite manufactured antennas, are under development as part of the SKA precursor telescopes being constructed at the two SKA sites, ASKAP in Western Australia (Deboer 2009) and MeerKAT in South Africa (Jonas 2009). These telescopes will begin astronomical observations by 2014/15. Focal-plane phased array systems are also being installed on the Westerbork Synthesis Radio Telescope (Verheijen 2008) to provide a factor of 25 increase in field of view. Low-frequency aperture plane array systems are achieving operational status for astronomy on the LOFAR facility (Vermeulen 2012).

The SKA builds on these technology advances. The new international SKA Organization has now begun a final detailed design phase (the so-called pre-construction phase) targeted to end in 2016. This phase will see prototypes of SKA technologies. For example, Figure 1 shows a rendering of a prototype SKA 15-m composite dish antenna that will be constructed in early 2013 at the Dominion Radio Astrophysical Observatory.
Table 1. Target SKA development and construction timeline

<table>
<thead>
<tr>
<th>Time</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 - 2011</td>
<td>Conceptual design (preparatory phase)</td>
</tr>
<tr>
<td>2011</td>
<td>Establish SKA organization for pre-construction</td>
</tr>
<tr>
<td>2012</td>
<td>Site decision</td>
</tr>
<tr>
<td>2012 - 2016</td>
<td>Detailed design (Pre-construction phase)</td>
</tr>
<tr>
<td>2016 - 2020</td>
<td>SKA phase 1 construction</td>
</tr>
<tr>
<td>2020</td>
<td>SKA phase 1 science operations</td>
</tr>
<tr>
<td>2020 - 2024</td>
<td>SKA phase 2 construction</td>
</tr>
<tr>
<td>2024</td>
<td>Science operations with full SKA</td>
</tr>
</tbody>
</table>

in Canada. The primary outcomes of the pre-construction work will be a construction ready design for the first phase of the SKA and an assessment of technical readiness of advanced instrumentation options for SKA phase 2. The full SKA will consist of ∼3000 15-m parabolic antennas distributed over an area with baselines extending to several thousand kilometres and operating up to a radiation frequency of 10 GHz. In addition, aperture-plane phased arrays will be used up to baselines of a few hundred kilometres to observe large areas of the sky instantaneously at low frequencies, from 70 MHz up to at least a few hundred MHz and potentially as high as a GHz.

SKA phase 1 will provide a sub-set of the full SKA capabilities, chosen to target at high priority two key science areas: pulsars and gravity, and the evolution of hydrogen from the dark ages to the present epoch. Phase I will have approximately 10% of the collecting area of the full SKA and will extend to baselines of a few hundred kilometres. The Phase 1 SKA Observatory will consist of three separate receptor arrays: an array of 250 dish antennas equipped with single-pixel feeds operating in the GHz range, an array of 90 dish antennas with focal-plane phased-array feeds operating from 0.7 - 1.8 GHz, and a low-frequency sparse aperture-plane phased array operating from 70 - 450 MHz.

Figure 1. Rendering of a prototype SKA 15-m composite material antenna under construction at the Dominion Radio Astrophysical Observatory in Penticton, Canada. The offset design optimizes for high dynamic range imaging by minimizing radiation scattered into feed. The focal structure will accommodate both single-pixel and focal-plane phased-array feed systems. (Image Credit: National Research Council of Canada, Canada/US-TDP SKA Dish Verification Project)
2.2. *The SKA observatory sites*

Following extensive technical studies, beginning in 2008, of proposed SKA sites in Australia/New Zealand and Southern Africa, the SKA Organization formally adopted a dual site option for the SKA in 2012. This option leverages the significant investment in infrastructure developments in both Western Australia and South Africa to provide an enhanced SKA phase I observatory. The distribution of the SKA observatory facilities for Phase I and Phase 2 is shown in Table 2. The 250-element high-sensitivity dish array will be constructed by adding 190 antennas to the MeerKAT located in the Karoo Desert in northern South Africa. In Western Australia the ASKAP telescope with focal-plane array feeds will be built out from 36 to 90 antennas, providing a power sky survey telescope for continuum and atomic hydrogen line emission. Western Australia will also host the first phase of the sparse aperture plane array for instantaneous all-sky imaging of high redshift HI and transient detection. These facilities provide complementary capabilities that are a major advance on current telescopes and together advance key science questions related to the epoch of re-ionization, transients, pulsars and gravity, and galaxy evolution.

Phase 2 of the SKA will see the extension of the dish array to baselines of several thousand kilometres through Southern Africa and the build out of the low-frequency sparse aperture plane array in Western Australia to its full collecting area early in the next decade. En-route to the distributed long-baseline remote stations for SKA Phase 2, a group of African nations is advancing the development of a network of antennas for an African VLBI network.

3. Conclusion

The Square Kilometre Array project is moving into a final detailed design and technology demonstration phase that will lead to the deployment of the first 10% of the SKA at sites in Western Australia and South Africa during the latter part of this decade. The sensitivity, field-of-view, broad-frequency range and imaging capabilities of this first phase of the SKA will begin a transformational advance over a broad range of astrophysics. Optimization for studies of pulsars, extreme gravity and gravitational waves, and of the evolution of neutral hydrogen are guiding the engineering design of SKA phase 1 - an important milestone on the pathway to the full SKA science operations in the decade to follow.

<table>
<thead>
<tr>
<th>Table 2. Summary of the dual-site deployment plan for the SKA Observatory Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SKA Phase 1 Deployment 2016-2020</strong></td>
</tr>
<tr>
<td>Phase 1 low-frequency aperture plane array</td>
</tr>
<tr>
<td>90-element sky survey dish antenna array with focal-plane phased-array feeds</td>
</tr>
<tr>
<td>250-element high-sensitivity dish antenna array with single-pixel feeds</td>
</tr>
<tr>
<td><strong>SKA Phase 2 Deployment 2020-2024</strong></td>
</tr>
<tr>
<td>Phase 2 low-frequency aperture plane array</td>
</tr>
<tr>
<td>3000-element dish antenna array with FPA and single-pixel feeds</td>
</tr>
<tr>
<td>Mid-frequency dense aperture array (^1)</td>
</tr>
</tbody>
</table>

Notes: \(^1\)Deployment of dense aperture plane array receptors for SKA Phase 2 is contingent on technical readiness.
Figure 2. The Phase 1 SKA Observatory will consist of dish and sparse aperture plane array technologies. Two dish antenna arrays, a high-sensitivity array equipped with single-pixel feeds in South Africa will operate up to 3 GHz and a second survey instrument with focal-plane phased arrays in Australia will image large instantaneous fields of view from 0.7 - 1.8 GHz. A separate low-frequency sparse aperture plane array at the Western Australia site, operating down to 70 MHz, will allow sensitive observations of highly redshifted neutral hydrogen emission. (Image credit: SKA Organization/Swinburne Astronomy Productions.)

References
Summary
Closing remarks

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This meeting started with a bang, with the announcement of what appears to be another 'Lorimer burst’. Two more ‘diamond planets’, white dwarf binary companions made of crystalline carbon, quickly followed. This drama in the first session gave way to numerous interesting, surprising results. We still have not found a pulsar orbiting a black hole, but we do have the first triple system with the pulsar in the inner binary and a main sequence star forming the outer part of the binary; it may allow tests of the Equivalence Principle. Another close binary may allow checking for dipolar gravitational radiation. Work on the spin-up of millisecond pulsars is better determining the mass accreted during the spin-up and more sophisticated determination of their ages. Indications of more high mass (\(\sim 2 M_\odot\)) pulsars will allow constraints to be placed on the Equation of State for a neutron star. As was remarked, 'We keep finding cool new pulsars wherever we look!'; Duncan Lorimer predicted we would know of 4000 pulsars by 2020, a doubling of the present number.

The 'empty' space in the P - P-dot diagram between the magnetars and 'normal' stars is being populated and the 'missing link' with low mass X-ray binaries is being filled in (along with a welcome magnetic field measurement from an X-ray cyclotron line). The Fermi satellite continues to be a rich source of new gamma ray pulsars, with a large fraction of them apparently radio quiet. The number of RRATs continues to grow, with consequent problems for the size of the total neutron star population; we now see that RRAT is a detection classification, not a separate population and that there must be an evolutionary linkage (yet to be revealed) between several groups of pulsars.

One of the striking developments in pulsar astrophysics over the last few years has been the discovery of the richness in timing noise. P-dot changes, nulling, mode-switching and polarization changes are found to be linked - at least in the stronger pulsars with the largest timing noise. 'Magnetospheric switching' is the new buzz phrase; it has memory and is surprisingly repeatable! To my mind it is another surprising factor to be added to an already complicated environment!

We are indebted to the many who have contributed to the success of this meeting; I recognize the presenters of the 75 oral papers, the similar number of lead authors on posters, the SOC, and other key figures thus†:

† Footage: http://www.pulsarastronomy.net/IAUS291/video/JocelynBellBurnell1/
A pulsar sound poem

Manchester, Buchner, Weber, Wang  
(At a steady pace)

Shibata, Gupta, Dembska, Tang
Possenti, Kaspi, Lee and Li.
Romani, Ransom, Özel, Rea
McLaughlin, Kramer, Jenet, Nice
Van Leeuwen, Shannon, Coenen Thijs,
Camero, Melrose, Lyne and Dyks
Spitkovsky, Seymour, Seo, Xie

Hick

Aris, Ellis, Cordes, Bailes  
(faster then)
Tauris, Lassus, Heras, Surnis  
(slowing to)
Roberts, Stappers, Hobbs and Flores,  
(original pace)
Falcke, Freire, Ferrand, Zane
Malov, Pavlov, Oskinova,
Wada, Na and Espinoza.

Smirnova, Yan, Petrova, Han  
(mode change)
Kohmura, Wu, Kameya, Yu
Kojima, Du, Fantina, Zhu
Tanaka, Xu, Urama too!
Karako, Zhang, Dall’Osso, Yang
Van Haaften, Lynch, Kholtygin, Lin,

Lorimer, Qiao, Hanbarayan, Aoki, Yuen, Igoshev,  
(quietly, no)
Zhou, Serylak, Cui, Chattopadhyay, Gao,  
rhythm
Camero-Arranz, Yuan, Huang, Lazarus, .....  
(end of null)

Van den Heuvel, Ali Alpar  
(loud with)
Kerr and Keene and Keith and Kirk  
beat
Cherry Ng, and Reisenegger

Siemion, Chamel, Guillemot, Sumiyoshi,  
(quietly, no)
Saz-Parkinson, Belfiore, Burke-Spolaor,  
rhythm
Rubio-Herrera, Degenaar, D’Angelo,
Andersson, J-P, Karastergiou, Liu, Poutanen, Desvignes, Safi-Harb, Chatterjee, Majid, Chanaangalam

Barnah, Kumar, Gajjar, Dai (loud with beat)
Johnston, Joshi, Shao, Lai
Feynman, Einstein, Hulse and Taylor
Baade, Zwicky, Volkoff, Tolman
Oppenh- eimer, Kondratiev, Gusev, Wex, (quietly, no pulse null)
van Kerkwijk, Scholz, Palucci, Pavlovskii rhythm
Ho, Timokhin, Eatough, Deng, Riles, Yue,
Stepanov, Tendulkar, Kisaka, Gentile, Török,
Tong, Ulyanov, Zhen end of null

What an utter, mutter, nutter! (slowly)
Wheeew (descending whistle) dispersion
Bonk

Thanks to the Organising Committees for such an excellent programme, and to the speakers and participants for making it such an interesting and enjoyable event. I was particularly grateful to our three Plenary speakers; sitting amongst the large audience of astronomers rather less familiar than us with pulsars, it was very satisfying to hear the amazed gasps as they appreciated the accuracy with which pulsar periods are measured and the consequences for physics of having such data. Thanks to all who welcomed us to China and smoothed our paths and special thanks to the conference volunteers, the orange-shirted students, who have been so helpful in ensuring everything went smoothly.

Acknowledgements

I thank the UK’s STFC, the Chinese Academy of Sciences, and Number 35 School Beijing for financial support.
Posters
High magnetic field pulsars with magnetar-like activity

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Abstract.
To study the origin of magnetars, a unique opportunity is provided by detecting an excess of X-ray thermal radiation of the radio pulsars (rotation powered pulsars) with dipolar magnetic fields as high as magnetars. The excess is probably caused by decay of the magnetic field as seen in magnetars. In order to investigate whether the rotation powered pulsars have the excess flux and the hard-tail component similar to magnetars, we observed PSR J0726-2612 which has a 3.44 s period and a $3 \times 10^{13}$ G inferred dipolar magnetic field, with Suzaku for 44 ks on 2011 November 16-17. We report this observational result. We also compare with other observations and discuss a decaying of the magnetic field for normal radio pulsars.
R-Process nucleosynthesis in high entropy environment in explosion of supernova type II and neutron star formation

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Abstract.

It is generally acknowledged that Type II supernovae result from the collapse of iron core of a massive star which, at least in some cases, produces a neutron star. At this stage, the neutrinos are produced by neutronization which speeds up as collapse continues. During collapse an outward bound shock wave forms in the matter falling onto the nearly stationary core. The conditions behind the shock at 100 to 200 km are suitable for neutrino heating. This neutrino heating blows a hot bubble above the protoneutron star and is the most important source of energy for Supernova explosion. At this stage, we try to attain the r-process (rapid neutron capture process) path responsible for the production of heavy elements beyond iron, which are otherwise not possible to be formed by fusion reactions. The most interesting evolution occurs as temperature falls from \(10^{10}\) K to \(10^9\) K. At these high temperature conditions, the critical fluids after fusion reactions are forbidden and transform into the respective atoms by r-process path which on beta decaying produce the ultimate elements of the periodic chart.

Another astrophysical parameter needed for our analysis is neutron number density which we take to be greater than \(10^{20}\) cm\(^{-3}\). With these, at different entropy environments, we assign the neutron binding energy that represents the r-process path in the chart of nuclides. Along the path, the experimental data of observed elements matches our calculated one. We find that an entropy of \(\sim 300\) with Ye \(\simeq 0.45\) can lead to a successful r-process. It produced heavy neutron-rich nuclei with \(A \simeq 80 - 240\). Later ejecta are neutron-rich (Ye \(\leq 0.5\)) and leaves behind a compact neutron star.
A new low-B magnetar: Swift J1822.3–1606

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Abstract.

We report on the long term X-ray monitoring with \textit{Swift}, \textit{RXTE}, \textit{Suzaku}, \textit{Chandra}, and \textit{XMM-Newton} of the outburst of the newly discovered magnetar Swift J1822.3–1606 (SGR 1822-1606), from the first observations soon after the detection of the short X-ray bursts which led to its discovery (July 2011), through the first stages of its outburst decay (April 2012). Our X-ray timing analysis finds the source rotating with a period of $P = 8.43772016(2)$ s and a period derivative $\dot{P} = 8.3(2) \times 10^{-14}$ s s$^{-1}$, which entails an inferred dipolar surface magnetic field of $B \simeq 2.7 \times 10^{13}$ G at the equator. This measurement makes Swift J1822.3–1606 the second lowest magnetic field magnetar (after SGR 0418+5729; Rea et al. 2010). Following the flux and spectral evolution from the beginning of the outburst, we find that the flux decreased by about an order of magnitude, with a subtle softening of the spectrum, both typical of the outburst decay of magnetars. By modeling the secular thermal evolution of Swift J1822.3–1606, we find that the observed timing properties of the source, as well as its quiescent X-ray luminosity, can be reproduced if it was born with a poloidal and crustal toroidal fields of $B_p \sim 1.5 \times 10^{14}$ G and $B_{\text{tor}} \sim 7 \times 10^{14}$ G, respectively, and if its current age is $\sim 550$ kyr (Rea et al. 2012).

Keywords. stars: magnetic fields — stars: neutron — X-rays: Swift J1822.3–1606
Figure 1. Left: Outburst model from Pons & Rea (2012) superimposed to the 1-10 keV flux decay of Swift J1822.3–1606. Black circles denote Swift/XRT data, red triangles correspond to XMM-Newton and blue stars to Suzaku/XIS03 data. Right: Pulse phase evolution as a function of time, together with the time residuals (lower panel) after having corrected for the linear component (correction to the $P$ value). The solid lines in the two panels mark the inferred $P–\dot{P}$ coherent solution based on the whole dataset, while the dotted lines represent the $P–\dot{P}$ coherent solution based on the data collected during the first 90 days only.

1. X-ray spectral modeling

In this study, we used all available data obtained from different space-based satellites, covering a time-span from July 2011 until end of April 2012. Spectra were extracted for all the RXTE/PCA, Swift/XRT, Suzaku/XIS03, and XMM–Newton/pn data, using standard software provided by the different team missions, and modeled using XSPEC version 12.7.0. Best fits were found using a blackbody plus power-law (BB+PL; $\chi^2/\text{dof} = 1.05/2522$) and a 2 blackbodies (2BBs; $\chi^2/\text{dof} = 1.06/2522$) model, all corrected for the photoelectric absorption. Figure 1 (left) shows how the flux decreased by about an order of magnitude, typical of the outburst decay of magnetars.

The aggressive monitoring campaign we present here allowed us not only to study in detail the flux decay of Swift J1822.3–1606, but also to give an estimate of its typical timescale. We have compared the observed outburst decay with the more physical theoretical model presented in Pons & Rea (2012). In addition, we have performed numerical simulations with a 2D code designed to model the magneto-thermal evolution of neutron stars. In Figure 1 (left), super-imposed, we show our best representative model that reproduces the observed properties of the decay of Swift J1822.3–1606 outburst. This model corresponds to an injection of $4 \times 10^{25}$ erg cm$^{-3}$ in the outer crust, in the narrow layer with density between $6 \times 10^8$ and $6 \times 10^{10}$ g cm$^{-3}$, and in an angular region of 35 degrees (0.6 rad) around the pole. The total injected energy was then $1.3 \times 10^{42}$ erg.

2. X-ray timing analysis

For the X-ray timing analysis we used all available data after barycentering all the events. We started by obtaining an accurate period measurement by folding the data from the first two XRT pointings which were separated by less than 1 day, and studying the phase evolution within these observations by means of a phase-fitting technique (see Dall’Osso et al. 2003 for details). The resulting best-fit period (reduced $\chi^2 = 1.1$ for 2 dof) is $P = 8.43966(2)$ s (all errors are given at 1σ c.l.) at the epoch MJD 55757.0. The
above period accuracy of 20\,µs is enough to phase-connect coherently the later \textit{Swift}, \textit{RXTE}, \textit{Chandra}, \textit{Suzaku}, and \textit{XMM-Newton} pointings (see Figure 1).

We modeled the phase evolution with a linear plus quadratic term. The corresponding coherent solution (valid until November 2011) is $P = 8.43772007(9)$\,s and period derivative $\dot{P} = 1.1(2) \times 10^{-13}$\,s\,s$^{-1}$ ($\chi^2 = 132$ for 57 dof at epoch MJD 55757.0). The above solution accuracy allows us to unambiguously extrapolate the phase evolution until the beginning of the next \textit{Swift} visibility window which started in February 2012. The final resulting phase-coherent solution, once the latest 2012 observations are included, returns a best-fit period of $P = 8.43772016(2)$\,s and period derivative of $\dot{P} = 8.3(2) \times 10^{-14}$\,s\,s$^{-1}$ at MJD 55757.0 ($\chi^2 = 145$ for 67 dof). The above best-fit values imply a surface dipolar magnetic field of $B \simeq 2.7 \times 10^{13}$\,G (at the equator), a characteristic age of $\tau_c = P/2\dot{P} \simeq 1.6$\,Myr, and a spin-down power $L_{\text{rot}} = 4\pi I \dot{P}/P^3 \simeq 1.7 \times 10^{30}$\,erg\,s$^{-1}$ (assuming a neutron star radius of 10\,km and a mass of 1.4\,$M_\odot$). The final solution has a relatively high r.m.s. (~120 ms) resulting in a best-fit reduced $\chi^2 = 2.1$. The $3\sigma$ upper limit of the second derivative of the period was $\ddot{P} < 5.8 \times 10^{-21}$\,s\,s$^{-2}$ (but see also Livingstone et al. 2011 and Scholz et al. 2012).

3. Conclusions

We have reported on the outburst evolution of the new magnetar Swift J1822.3–1606, which, despite its relatively low magnetic field ($B = 2.7 \times 10^{13}$\,G), is in line with the outbursts observed for other magnetars with higher dipolar magnetic fields.

We found that the current properties of the source can be reproduced if it has now an age of ~550 kyr, and it was born with a toroidal crustal field of $7 \times 10^{14}$\,G, which has by now decayed by less than an order of magnitude.

The position of Swift J1822.3–1606 in the $P$–$\dot{P}$ diagram is close to that of the “low” field magnetar SGR 0418+5729 (Rea et al. 2010). As argued in more detail in Rea et al. (2012), we note that the discovery of a second magnetar-like source with a magnetic field in the radio-pulsar range strengthens the idea that magnetar-like behavior may be much more widespread than what believed in the past, and that it is related to the intensity and topology of the internal and surface toroidal components, rather than only to the surface dipolar field (Rea et al. 2010, Perna & Pons 2011, Turolla et al. 2011).

References

Does a hadron-quark phase transition in dense matter preclude the existence of massive neutron stars?

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Abstract. We study the impact of a hadron-quark phase transition on the maximum neutron-star mass. The hadronic part of the equation of state relies on the most up-to-date Skyrme nuclear energy density functionals, fitted to essentially all experimental nuclear mass data and constrained to reproduce the properties of infinite nuclear matter as obtained from microscopic calculations using realistic forces. We show that the softening of the dense matter equation of state due to the phase transition is not necessarily incompatible with the existence of massive neutron stars like PSR J1614−2230.

Keywords. stars: neutron, dense matter, equation of state, stars: interiors, gravitation

1. Introduction

Neutron stars (NSs) result from the gravitational collapse of massive stars with $M \gtrsim 8M_\odot$ at the end point of their evolution. They are among the most compact objects in the universe, with a central density which can reach several times the nuclear saturation density. At least, three different regions can be identified in the interior of a neutron star: (i) the “outer crust”, at densities above $\sim 10^4$ g cm\(^{-3}\), composed of fully ionized atoms, arranged in a Coulomb lattice of nuclei, neutralized by a degenerate electron gas, (ii) the “inner crust”, at densities above $\sim 4 \times 10^{11}$ g cm\(^{-3}\), composed of neutron-proton clusters and unbound neutrons, neutralized by a degenerate electron gas, and (iii) the core, at densities above $\sim 10^{14}$ g cm\(^{-3}\). The precise measurement of the mass of pulsar PSR J1614−2230 by Demorest et al. (2010) has revived the question of the composition of the core. Just below the crust, the matter consists of a mixture of neutrons, protons, electrons and possibly muons. The composition of the central region of a NS is still a matter of debate (see e.g. Haensel et al. 2007).

In the present work, we study the impact of a hadron-quark phase transition in dense matter on the maximum mass of cold isolated NSs (see Chamel et al. 2012 for a general discussion of the maximum mass of hybrid stars).

2. Hadronic equation of state

The global structure of a NS is determined by the equation of state (EoS), i.e. the relation between the matter pressure $P$ and the mass-energy density $\rho$. Before considering the possibility of a phase transition from hadronic to quark matter in the core of NSs, we will begin with the hadronic EoSs. A good starting point is the family of three EoSs, BSk19, BSk20 and BSk21, which have been developed to provide a unified treatment of all regions of a NS (see Pearson et al. 2011, Pearson et al. 2012). These EoSs are based
on nuclear energy-density functionals derived from generalized Skyrme forces (in that they contain additional momentum- and density-dependent terms), which fit essentially all measured masses of atomic nuclei with an rms deviation of 0.58 MeV for all three models. Moreover, these functionals were constrained to reproduce three different neutron matter EoSs, as obtained from microscopic calculations (see Goriely et al. 2010). All three EoSs assume that the core of a NS is made of nucleons and leptons. The BSk19 EoS was found to be too soft to support NSs as massive as PSR J1614–2230 (Chamel et al. 2011) and therefore, it will not be considered here.

3. Hadron-quark phase transition

Given the uncertainties in the composition of dense matter in NSs, we will simply suppose that above the average baryon density \( n_N \), matter undergoes a first-order phase transition to deconfined quark matter subject to the following restrictions: (i) for the transition to occur the energy density of the quark phase must be lower than that of the hadronic phase, (ii) according to perturbative quantum chromodynamics (QCD) calculations (e.g. Kurkela et al. 2010), the speed of sound in quark matter cannot exceed \( c/\sqrt{3} \) where \( c \) is the speed of light. At densities below \( n_N \), matter is purely hadronic while a pure quark phase is found at densities above some density \( n_X \). In the intermediate region \( (n_N < n < n_X) \) where the two phases can coexist, the pressure and the chemical potential of the two phases are equal: \( P_{\text{quark}}(n) = P_{\text{hadron}}(n_N) \) and \( \mu_{\text{quark}}(n) = \mu_{\text{hadron}}(n_N) \). The EoS of the quark phase at \( n > n_X \) is given by:

\[
P_{\text{quark}}(n) = \frac{1}{3}(E_{\text{quark}}(n) - E_{\text{quark}}(n_X)) + P_{\text{hadron}}(n_N).
\]

We set the density \( n_N \) to lie above the highest density found in nuclei as predicted by Hartree-Fock-Bogoliubov calculations, namely \( n_N = 0.2 \text{ fm}^{-3} \) (BRUSLIB). The density \( n_X \) is adjusted to optimize the maximum mass under the conditions mentioned above. Eq. (3.1) turns out to be very similar to that obtained within the simple MIT bag model, which has been widely applied to describe quark matter in compact stars (see e.g. Haensel et al. 2007). The effective bag constant \( B \) associated with the BSk21 hadronic EoS is 56.7 MeV fm\(^{-3}\).

4. Maximum mass

Considering the stiffest hadronic EoS (BSk21), we have solved the Tolman-Oppenheimer-Volkoff equations (Tolman 1939, Oppenheimer & Volkoff 1939) in order to determine the global structure of a non-rotating neutron star. The effect of rotation on the maximum mass was found to be very small for stars with spin-periods comparable to that of PSR J1614–2230 (Chamel et al. 2011); we therefore neglect it. The gravitational mass versus circumferential radius relation is shown in Fig. 1. We have considered two cases: a purely hadronic neutron star described by our BSk21 EoS (dashed line) and a hybrid star with a quark core (solid line). The corresponding maximum masses are 2.28 \( M_\odot \) and 2.02 \( M_\odot \) respectively. In both cases, the existence of two-solar mass NSs is therefore allowed.

5. Conclusions

The presence of a deconfined quark-matter phase in NS cores leads to a maximum mass of about 2\( M_\odot \), which is still compatible with the mass measurement of PSR J1614–2230.
Figure 1. Gravitational mass versus circumferential radius with (solid line) and without (dashed line) a quark-matter core. See the text for detail.

by Demorest et al. (2010), but which could be challenged by observations of significantly more massive NSs (see Clark et al. 2002, Freire et al. 2008, van Kerkwijk et al. 2011) unless the sound speed in quark matter is significantly larger than that predicted by perturbative QCD calculations (Kurkela et al. 2010).

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Oppenheimer, J. R., & Volkoff, G. M. 1939, Phys. Rev., 55, 374
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Unified description of dense matter in neutron stars and magnetars

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Abstract. We have recently developed a set of equations of state based on the nuclear energy density functional theory providing a unified description of the different regions constituting the interior of neutron stars and magnetars. The nuclear functionals, which were constructed from generalized Skyrme effective nucleon-nucleon interactions, yield not only an excellent fit to essentially all experimental atomic mass data but were also constrained to reproduce the neutron-matter equation of state as obtained from realistic many-body calculations.

Keywords. stars: neutron, dense matter, equation of state, gravitation, magnetic fields, stars: interiors

1. Introduction

With a mass of the order of that of our Sun compressed inside a radius of about 10 km only, neutron stars (NS) are among the most compact objects in the universe (see e.g. Haensel et al. 2007). Their central density can exceed several times the density encountered in the heaviest atomic nuclei. NS are also the most strongly magnetized objects. Surface magnetic fields of order $10^{14} - 10^{15}$ G have been estimated in soft gamma-ray repeaters and anomalous X-ray pulsars assuming that their spin-down is due to magnetic dipole radiation (see e.g. McGill SGR/AXP online catalog). In addition, circumstantial evidence of surface magnetic fields greater than $10^{15}$ G have been reported from spectroscopic studies (see e.g. Strohmayer & Ibrahim 2000, Gavriil et al. 2002, Woods et al. 2005). The internal magnetic field of a NS could be even stronger than its surface field, as found in the Sun (see e.g. Solanki et al. 2006). In particular, according to the magnetar model of Thompson & Duncan (1993), magnetic fields up to $\sim 10^{17}$ G could be generated via dynamo effects in hot newly-born NS.

The outer crust of a cold non-accreting NS is primarily composed of pressure ionized iron atoms arranged in a regular crystal lattice and embedded in a highly degenerate electron gas. With increasing density, nuclei become more and more neutron-rich due to electron captures. Eventually, at a density $\sim 4 \times 10^{11}$ g/cm$^3$, some neutrons start to drip out of nuclei, thus defining the boundary between the outer crust and the inner crust. At densities above $\sim 10^{14}$ g/cm$^3$, the crust dissolves into a uniform plasma of nucleons and leptons. The composition of the core remains very uncertain.

We have determined the internal structure a cold non-accreting NS endowed with a
strong magnetic field using a unified treatment of dense matter based on the nuclear energy-density functional (EDF) theory.

2. Brussels-Montreal equations of state

The EDF theory provides a self-consistent description of various nuclear systems, from finite nuclei to homogeneous nuclear matter. It is therefore well suited for studying the interior of a NS. The Brussels-Montreal EDF BSk19, BSk20 and BSk21 were derived from generalized Skyrme effective nucleon-nucleon interactions which fit essentially all measured masses of atomic nuclei (calculated using the Hartree-Fock-Bogoliubov method) with an rms deviation as low as 0.58 MeV. In addition, these EDF were constrained to reproduce three different representative neutron-matter equations of states (EoSs) obtained from microscopic calculations using realistic two- and three- body forces and reflecting the current lack of knowledge of dense neutron matter (see Goriely et al. 2010).

We used these EDF to calculate consistently the properties of all regions of the interior of a non-accreting NS, from its surface down to the center, under the assumption of cold catalyzed matter (see Pearson et al. 2011, Pearson et al. 2012). The core was assumed to be made of nucleons and leptons only. The resulting unified EoSs are consistent with the radius constraints of Steiner et al. (2010) inferred from observations of X-ray bursters and low-mass X-ray binaries (Fantina et al. 2011). However, only the EoSs based on the BSk20 and BSk21 EDF are stiff enough at high densities to support NS as massive as PSR J1614−2230 (see Chamel et al. 2011).

3. Internal structure of magnetars

The internal composition of a magnetar can be substantially different from that of an ordinary NS, especially in the outermost layers. We have therefore recalculated the EoS of the outer crust of a NS taking into account the presence of the magnetic field using the BSk21 EDF (see Chamel et al. 2012). In a strong magnetic field, the electron motion perpendicular to the field is quantized into Landau levels and this can change the sequence of equilibrium nuclides. We have found that the deviations become particularly significant for \( B \sim 10^{16} \) G. Moreover, strong magnetic fields tend to prevent neutrons from dripping out of nuclei thus increasing the pressure at which the neutron drip transition occurs. The effects of the magnetic field on nuclei, which we have neglected, could also have an impact on the crust for \( B \gtrsim 10^{17} \) G (Peña Arteaga et al. 2011).

Strong magnetic fields can change the EoS in the surface regions where only a few Landau levels are filled. However, with increasing density the effects of \( B \) become less and less important as more and more levels are populated and the EoS matches smoothly with that obtained for \( B = 0 \). For \( B \sim 10^{15} \) G, only the EoS in the outer crust is affected. Therefore the global structure of a magnetar would be almost undistinguishable from that of an ordinary NS.

4. Conclusions

We have developed a series of EoSs of cold catalyzed matter based on the EDF theory and describing consistently all regions of a cold non-accreting NS (Chamel et al. 2011). These EoSs have been recently extended to magnetars by taking into account the effects of the strong magnetic field in the outer crust (Chamel et al. 2012). We have found that the outer crust of a magnetar could have a substantially different composition (hence also different properties) compared to that of an ordinary NS.
Table 1. Sequence of equilibrium nuclides with increasing depth in the outer crust of a cold non-accreting magnetar endowed with a magnetic field $B = 10^{17}$ G. For comparison, the results obtained for $B = 0$ are also indicated.

<table>
<thead>
<tr>
<th>$B = 10^{17}$ G</th>
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<td>$^{56}$Fe</td>
<td>$^{56}$Fe</td>
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<tr>
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<td>$^{86}$Sr</td>
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<td>$^{84}$Kr</td>
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<tr>
<td>$^{84}$Se</td>
<td>$^{84}$Se</td>
</tr>
<tr>
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<tr>
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<td>$^{132}$Sn</td>
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<td>$^{120}$Cd</td>
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<tr>
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Relativistic strange stars with anisotropy and B-parameter in pseudo spheroidal space-time

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Abstract. A class of compact cold stars in the presence of strange matter is obtained for a pseudo-spheroidal geometry. Considering the strange matter equation of state \(p = \frac{1}{3}(\rho - 4B)\), with pressure anisotropy described by Vaidya-Tikekar metric, we determine the parameter \(B\) both inside and on the surface of the star for different values of anisotropy parameter \(\alpha\). In the anisotropic case, we note that a stable model of a compact star may be realized.

Keywords. equation of state

1. Introduction

In relativistic astrophysics, the estimated masses and radii for many compact objects are not compatible with the standard neutron star models. To understand the behaviour of observed physical features of such compact objects, it has been predicted that strange quark matter may be a useful approach (Li et al. 1995; Bombaci 1997). In the case of compact objects an alternative approach was adopted (Mukherjee et al. 1997) to study the variation of pressure \(p\) and density \(\rho\) inside the stars based on the model (Vaidya & Tikekar 1982; Tikekar & Thomas 1999) with specific ansatz \(e^{2\nu} = \frac{1 + \lambda r^2/R^2}{1 + r^2/R^2}\) (\(\lambda =\) spheroidicity and \(R=\) Curvature parameter), prescribing 3-pseudo spheroidal geometries for the 3-space of the interior space-time of the star. The equation of state for the strange quark matter from Kapusta (1994) is:

\[
p = \frac{1}{3}(\rho - 4B)
\]  

where \(B\) is referred to as the Bag constant. The total energy density is \(\rho = \rho_q + B\) and total pressure is \(p = p_q - B\).

2. Anisotropic compact star model

The metric of a spherically symmetric, static, cold compact star in equilibrium is represented by,

\[
ds^2 = -e^{2\nu(r)}dt^2 + e^{2\mu(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)
\]  

where \(\nu(r)\) and \(\mu(r)\) are the two unknown metric functions. The energy-momentum tensor for the interior matter content of the ultra compact star with anisotropic fluid pressure is given by, \(T_{ij} = \text{diag} (-\rho, p_r, p_{\perp}, p_{\perp})\), where \(\rho\), \(p_r\) and \(p_{\perp}\) are the energy-density, radial pressure and tangential pressure respectively. In this model, pressure anisotropy.
(Tikekar & Thomas 1999) is defined as $\Delta = p_\perp - p_r$, which depends on metric functions $\mu(r)$ and $\nu(r)$. The Einstein field equation is,

$$\mathbf{R}_{ij} - \frac{1}{2}g_{ij}\mathbf{R} = T_{ij} \tag{2.2}$$

where $\mathbf{R}_{ij}$ is Ricci tensor and $\mathbf{R}$ is the Ricci scalar. Using Eq. (2.1) in Eq. (2.2), we obtain the following equations:

$$\rho = \left(1 - e^{-2\mu}\right) + \frac{2\mu' e^{-2\mu}}{r} \tag{2.3}$$

$$p_r = \frac{2\mu' e^{-2\mu}}{r} - \frac{\left(1 - e^{-2\mu}\right)}{r^2} \tag{2.4}$$

$$\Delta e^{2\mu} = \left[\nu'' + \nu' + \nu' - \frac{2\mu'}{r} - \frac{(1 - e^{-2\mu})}{r^2}\right]. \tag{2.5}$$

To simplify we choose the anisotropy parameter $\Delta$ defined above as

$$\alpha = \frac{\Delta R^2 (1 - \lambda + \lambda x^2 z^2)}{\lambda (z^2 - 1)}$$

so that the regularity in pressure ($p$) and density ($\rho$) at the center of the star is ensured.

Now using Eqs. (2.4), (2.5) and the ansatz $e^{2\mu} = \frac{1 + \lambda x^2 / R^2}{1 + r^2 / R^2}$, one obtains a second order differential equation in 'z' (Mukherjee et al. 1997) given by,

$$\left(1 - z^2\right)\Psi_{zz} + z\Psi_z + \left(\beta^2 - 1\right)\Psi = 0 \tag{2.6}$$

where $|\beta|^2 = (2 - \lambda + \lambda \alpha)$, $z = \sqrt{\lambda/(\lambda - 1)}x$ with $x^2 = 1 + \frac{z^2}{R^2}$ and $\Psi = e^{\nu(r)}$. General solutions of Eq. (2.6) are given below:

**Case(i)** Here $\beta = \sqrt{2 - \lambda(1 - \alpha)}$ is positive for the values of $\lambda$ and $\alpha$. The solution is

$$\Psi = C[\beta \sqrt{z^2 - 1} \cosh(\beta \eta) - z \sinh(\beta \eta)] + D[\beta \sqrt{z^2 - 1} \sinh(\beta \eta) - z \cosh(\beta \eta)] \tag{2.7}$$

**Case(ii)** Here $\beta = \sqrt{\lambda(1 - \alpha - 2)}$ is positive for the values of $\lambda$ and $\alpha$. The solution is

$$\Psi = C[\beta \sqrt{z^2 - 1} \cos(\beta \eta) - z \sin(\beta \eta)] + D[\beta \sqrt{z^2 - 1} \sin(\beta \eta) - z \cos(\beta \eta)] \tag{2.8}$$

where $z = \cosh(\eta)$. $C$ and $D$ are two unknown constants. For an isotropic case ($\alpha = 0$), it reduces to the solutions obtained by Tikekar & Jotania (2005).

### 3. Discussion

The variation of energy density and pressure inside a compact stellar object can be understood qualitatively in this model from Eqs. (2.3) and (2.4). The energy density $\rho$ and radial pressure $p_r$ become:

$$\rho = \frac{1}{R^2(z^2 - 1)} \left[1 + \frac{2}{(\lambda - 1)(z^2 - 1)}\right] \tag{3.1}$$

$$p_r = -\frac{1}{R^2(z^2 - 1)} \left[1 - \frac{2z}{(\lambda - 1)}\Psi_z\right] \tag{3.2}$$

Using the expression of $\rho$ and $p_r$, the parameter $B$ may now be evaluated from Eq. (1.1). Here the unit of $B$ is $Mev/fm^3$ when $R$ is expressed in km. The following conditions may be imposed for a compact star: (i) At the boundary of the star Schwarzchild's exterior
solution is matched with the interior solution i.e.

\[ e^{2\nu(r=b)} = e^{-2\mu(r=b)} = \left(1 - \frac{2M}{b}\right) \tag{3.3} \]

(ii) Inside the star radial pressure \( p_r > 0 \), which leads to an inequality \( \frac{\psi_z}{\nu} < \frac{(\lambda-1)}{2z^2} \). However at \( r = b \) (defines the boundary of the star), the radial pressure \( p_r = 0 \), which yields \( \frac{\psi_z(z_b)}{\nu(z_b)} = \frac{(\lambda-1)}{2z_b^2} \), where \( z_b^2 = \frac{\lambda(1+k^2/R^2)}{(\lambda-1)} \). Now \( R \) can be evaluated using Eq. (3.2) for specific configuration of the compact object. To determine the role of anisotropy on \( B \), we determine the two unknown parameters \( C \) and \( D \) that appear in Eqs. (2.7) and (2.8) from matching condition. Once \( C \), \( D \) and \( R \) are known, the parameter \( B \) can be determined using Eq. (3.1) at different points in the star for different \( \alpha \) and \( \lambda \).

**Case I:** The data for X-ray pulsar Her X-1 are mass \( M = 0.88 \, M_\odot \), and radius \( b = 7.7 \) km, so that compactness \( u = M/b = 0.1686 \), \( R = 3.26376 \) km for \( \lambda = 1.6 \). Inside the star the value of \( B \) decreases from center to surface for a particular choice of \( \alpha \) and \( \lambda \). At the center \( B_0 = 86.2771 \) Mev/fm\(^3\) for \( \alpha = 0 \), \( B_0 = 143.067 \) Mev/fm\(^3\) for \( \alpha = 0.15 \) and \( B_0 = 4.81202 \) Mev/fm\(^3\). At the surface it attains a constant value \( B_b \) independent of the anisotropy parameter \( \alpha \). The data for SAX J 1808.4-3658 are mass \( M = 1.323M_\odot \) and radius \( b = 6.55 \) Kms, of radius \( R = 4.2668 \) Kms for \( \lambda = 3.1 \). \( B_0 = -2.55601 \) Mev/fm\(^3\) for \( \alpha = 0 \), \( B_0 = 125.271 \) Mev/fm\(^3\) for \( \alpha = 0.3 \), and \( B_0 = 7.09937 \) Mev/fm\(^3\). From the analysis for both cases it appears that \( B \) parameter picks up smaller values for isotropic case and increases in the presence of anisotropy. At the center of the star the value of \( B_0 \) is found to increase almost linearly with an increase of anisotropy \( \alpha \).

<table>
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<tr>
<th>( M/b )</th>
<th>0.15</th>
<th>0.20</th>
<th>0.24</th>
<th>0.28</th>
<th>0.30</th>
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<td>2.1400</td>
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<td>1.7194</td>
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<td>0.9344</td>
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<td>2.5665</td>
<td>2.4873</td>
<td>2.2587</td>
<td>2.1565</td>
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<tr>
<td>( B_b )</td>
<td>1.4062</td>
<td>1.1550</td>
<td>1.0000</td>
<td>0.5200</td>
<td>0.3550</td>
</tr>
</tbody>
</table>

**Table 1.** Variation of parameter \( B \) at the center (\( B_0 \)) and surface (\( B_b \)) in unit of Mev/fm\(^3\) with compactness factor \( (M/b) \) for \( \lambda = 5 \).

From Table 1 it is evident that at the surface of the star \( B_b \) decreases with an increase of compactness \( (M/b) \) for fixed \( \alpha \). It is also noted that \( B \) becomes negative near the centre of the star implying the core-region of such configurations to be repulsive. Thus the radial dependence of \( B \) parameter in presence of isotropic and anisotropic strange matter are different throughout the interior of the star although at the boundary it attains a definite value.

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Pulsar time scale and its future application

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Abstract. An Ensemble Pulsar Time Scale (EPT) is derived based on the Pulsar Timing Array. It is interesting to compare the EPT with the TT terrestrial time scale, and get many new realization on the pulsar time scale and the algorithm. Some future interesting applications of the EPT are described and discussed.
New timing solutions for RRATs

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Abstract. The rotating radio transients are sporadic pulsars which are difficult to detect through periodicity searches. By using a single-pulse search method, we can discover these sources, measure their periods, and determine timing solutions. Here we introduce our results on six RRATs based on Parkes and Green Bank Telescope (GBT) observations, along with a comparison of the spin-down properties of RRATs and normal pulsars.

Keywords. Pulsars: individual, stars: kinematics, stars: rotation

1. Introduction

Rotating Radio Transients (RRATs) are pulsars from which we detect only sporadic radio bursts, making them difficult to detect in traditional periodicity searches (McLaughlin et al. 2006). They were first discovered through single-pulse search reprocessing of the Parkes Multibeam Pulsar Survey data. Currently \(\sim 70\) of these sporadic pulsars are known. For these, we can calculate times-of-arrival and determine timing solutions, by using single pulses instead of the commonly used folded profiles. Timing solutions are crucial to understand their relation to other pulsars and the nature of their emission.

Here we introduce our results for six RRATs, along with a comparison between RRATs and normal pulsars. Five of these RRATs were discovered in a re-analysis of the Parkes Multibeam Survey data and one was discovered through a GBT drift-scan survey.

2. Single-pulse search

Classical search algorithms based on Fourier techniques or folding do not detect RRATs. In stead we search for individual pulses with signal-to-noise ratio above some threshold (typically \(5\sigma\)) in a number of trial-DM time series. Then, once a RRAT is discovered, the first step in our timing analysis is to identify which pulses are from the RRAT. We do this by searching for pulses which are brighter at the DM of the RRAT than at zero DM. Figure 1 shows an example of the single-pulse search output for a nearly one-hour observation of PSR J1048\textsuperscript{−}5838. We see very bright bursts peaking at DM of 69 pc/cm\(^3\) which differ from the signals peaking at DM of 0 pc/cm\(^3\) that are due to radio frequency interference (RFI). The pulsar only turns ‘on’ for six minutes of this observation.

3. Timing solutions

To get a timing solution for a RRAT, we must first calculate the spin period. We do this by measuring differences between pulse arrival times and calculating the greatest common denominator. Once a period is known, we bin the data into single pulse periods and
calculate times-of-arrival (TOAs) as the peak for each detected pulse. We have calculated timing solutions for six RRATs. PSR J1048−5838 has the longest span of observation of these RRATs: four years of post-discovery timing observations and a 13-year span including the discovery. Note that this RRAT was found in an even later reprocessing of the Parkes Multibeam Survey after the initial RRATs (Keane 2010). The timing residuals show good phase connection to its earlier discovery. We have calculated timing solution for this and five other RRATs. The periods are: 1.231 s (PSR J1048−5838), 0.503 s (PSR J1623−0841), 1.818 s (PSR J1739−2521), 1.320 s (PSR J1754−3014), 0.933 s (PSR J1839−0141), and 0.414 s (PSR J1848−1243). They have surface magnetic fields ranging from $4 \times 10^{11}$ G to $4 \times 10^{12}$ G, spin-down luminosities ranging from $2 \times 10^{30}$ ergs s$^{-1}$ to $6 \times 10^{32}$ ergs s$^{-1}$, and characteristic ages ranging from 1.6 Myr to 15 Myr.†

4. Pulse profiles and long timescale periodicities

Profiles of the six RRATs are presented in Figure 2. Here, pulse profiles of PSRs J1739−2521 and J1839−0141 are sums of data during the ~minute-long time periods when the RRATs are ‘on’. The profile of PSR J1048−5838 is a sum of all detected

† Latest RRAT solutions can be found in RRATalog: [www.as.wvu.edu/~pulsar/rratalog](http://www.as.wvu.edu/~pulsar/rratalog)
Figure 3. $P - \dot{P}$ diagram of solved RRATs and pulsars. New RRATs are shown as red stars and previously timed RRATs as blue stars. The black squares are magnetars, and black diamonds indicate X-ray isolated neutron stars. Lines of constant magnetic field (dashed) and characteristic age (dot-dashed) are shown. The KS test gives $1.12 \times 10^{-19}$, $2.45 \times 10^{-4}$, $1.94 \times 10^{-5}$, 0.16 and 0.04 probabilities that the period, period derivative, magnetic field, and characteristic age, spin-down energy-loss rate, respectively, were derived from the same distribution as those for other pulsars.

individual single pulses. The other profiles are created by folding each observation and summing all the profiles. Note that these three objects (PSRs J1623–0841, J1754–3014 and J1848–1243) were detected through single-pulse searches but are typically detectable in follow-up observations by folding all of the data. It is clear that the RRATs are a diverse group of objects with varying properties.

We have applied Lomb-Scargle analysis (Scargle 1982) on the unevenly sampled pulse arrival times of PSR J1048–5838 to see if there are any periodicities in the timeseries. The spectrum gives the most significant periodic signal to be of period 19.15 hours with significance level of 1.95 $\sigma$. This is much lower significance than the periodicities of similar timescale reported by Palliyaguru et al. (2011) for other RRATs.

5. Population of RRATs: Why different?

At this time, 21 of roughly 70 RRATs have timing solutions with period and period derivative, shown on the $P - \dot{P}$ diagram in Figure 2. We applied the Kolmogorov-Smirnov test (KS test) to the RRAT and normal pulsar populations to see how their spin-down properties compare (see Figure 2). The largest differences between the two groups are found in the distributions of period and magnetic field. While selection effects may be responsible for some of the period dependence, as longer period pulsars are more likely to be detected with higher signal-to-noise ratio in single-pulse searches (McLaughlin & Cordes 2003), the difference in period derivative distributions hints that there is a fundamental difference in these populations.

References

Microlensing pulsars
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Abstract.
We propose to determine the mass of isolated neutron stars through gravitational microlensing. We show that the all-sky microlensing pulsar event rate is $\sim 2.8 \times 10^{-10}$ per year per background source (/yr/source). Microlensing neutron star event rate would contribute $\sim 20\%$ to the total Galactic event rate at time-scale of $\sim 15$ days. We also present catalogue comparisons between known pulsars and background stars. We find that several pulsars would pass by background stars closely and may cause observable astrometric microlensing phenomenon. According to our covariance analysis, the uncertainty of masses determined through astrometric microlensing could be $\sim 20\%$. Therefore, gravitational microlensing is a promising way to determine the mass of isolated neutron stars with future advanced radio and optical telescopes.

Keywords. gravitational lensing, pulsars: general, stars: neutron

1. Introduction
The measurement of neutron star masses is essential to understand the inner structure of neutron stars and the state of dense matter at nuclear density. However, up to now, all accurate mass measurements are from observations of binary pulsars. As for isolated neutron stars, the mass measurement is still challenging. Gravitational microlensing has been suggested to measure the mass of isolated neutron stars (e.g., Dai et al. 2010). Future advanced radio and optical telescopes will greatly enhance the possibility of discovering microlensing pulsar events.

In Dai & Xu (2013, in prep.) we show that the all-sky microlensing pulsar event rate is $\sim 2.8 \times 10^{-10}$ /yr/source, and it could be 100 times larger for astrometric microlensing. Considering the kick velocity, the fractional contribution of microlensing neutron star event rate to the total Galactic event rate could be up to $\sim 20\%$ at time-scale of $\sim 15$ days. Therefore, it is hopeful to discover microlensing pulsar events. We also present catalogue comparisons between known pulsars, microlensing candidates and background stars. We find that several known pulsars would pass by background stars closely and may cause observable astrometric microlensing phenomenon. The covariance analysis of the simulated observations shows that the masses of neutron stars can be determined accurate to $\sim 20\%$.

2. Event rates and time-scale distributions
We calculated the microlensing pulsar event rates, based on the spatial and velocity distribution of pulsars (Faucher-Giguère & Kaspi 2006). For bulge, the all-sky event rate is $\sim 1.1 \times 10^{-10}$ /year/source, and for disk, it is $\sim 1.7 \times 10^{-10}$ /year/source. The total event rate is $\sim 2.8 \times 10^{-10}$ /year/source, and it could be $\sim 100$ times larger for astrometric microlensing since the cross-section of astrometric microlensing is much larger than that of photometric microlensing. On the other hand, considering the kick velocity of neutron
stars, we show that the fractional contribution of microlensing neutron star event rate to the total Galactic event rate could be up to $\sim 20\%$ at time-scale of $\sim 15$ days (see Fig 2). Surveys such as LSST will discover huge amounts of microlensing events, then it is possible to search pulsars among those short duration events and determine their masses at the same time.

3. Catalogue comparison

First, we compared the positions of pulsars and that of microlensing candidates. We used the ATNF pulsar catalogue (Manchester et al. 2005), which contains 2008 pulsars. The positions of microlensing candidates are from the published results of EROS (Hamadache et al. 2006), MACHO (Thomas et al. 2005), MOA† and OGLE (Udalski 2003). We found no known pulsars associated with identified microlensing candidates. Next, we carried out catalogue comparisons between known pulsars, SDSS and UKIDSS sources. We found that several pulsars would pass by background stars closely and may cause observable astrometric microlensing phenomenon. In Table 1, we list relevant information of pulsars and their associated background sources with maximum centroid shift larger than 100 $\mu$as.

We used covariance analysis to estimate the uncertainty of masses determined through astrometric microlensing phenomenon. In Fig 1, we show the percentage error of Einstein

† http://www.phys.canterbury.ac.nz/moa/index.html

<table>
<thead>
<tr>
<th>Pulsar ID(UKIDSS)</th>
<th>Current centroid shift ($\mu$as)</th>
<th>Maximum centroid shift ($\mu$as)</th>
<th>$t_0$ (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1910+1256</td>
<td>438685156132</td>
<td>277(171)</td>
<td>551(9)</td>
</tr>
<tr>
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<td>438809433778</td>
<td>216(35)</td>
<td>35(0.03)</td>
</tr>
<tr>
<td>J1835-1106</td>
<td>438519400030</td>
<td>173(151512)</td>
<td>-47(130)</td>
</tr>
<tr>
<td>B1829-08</td>
<td>438747104229</td>
<td>146(8869)</td>
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</tr>
<tr>
<td>B1952+29</td>
<td>438604464609</td>
<td>124(233)</td>
<td>42(13)</td>
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</table>

Table 1. Pulsars and background sources with maximum centroid shift larger than 100 $\mu$as.

Figure 1. Fractional contribution of microlensing neutron stars event rate to the total Galactic event rate, as a function of the event time-scale. The solid and dashed lines represent calculations considering the kick velocity of neutron stars and without considering, respectively.
radius as a function of number of data points for a typical microlensing pulsar event. With the definition of Einstein radius, \( \theta_E \sim \sqrt{\frac{4GM(D_s-D_d)}{c^2D_sD_d}} \), and taking the uncertainty of Einstein radius and distance to pulsars to be 5% and 10%, respectively, we can determined the masses of pulsars accurate to \( \sim 20\% \).

4. Conclusion

Gravitational microlensing could be a promising way to determine the mass of isolated neutron stars. The all-sky microlensing pulsar event rate is \( \sim 2.8 \times 10^{-10} \) /year/source, and it could be much larger for astrometric microlensing. Considering the kick velocity, microlensing neutron star events could contribute up to \( \sim 20\% \) of Galactic events at time-scale of \( \sim 15 \) days. Catalogue comparisons between known pulsars and background stars showed that several pulsars may cause observable astrometric microlensing phenomenon, and the masses can be determined accurate to \( \sim 20\% \).

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References

Constraints on Yukawa parameters by double pulsars

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Abstract. Although Einstein’s general relativity has passed all the tests so far, alternative theories are still required for deeper understanding of the nature of gravity. Double pulsars provide us a significant opportunity to test them. In order to probe some modified gravities which try to explain some astrophysical phenomena without dark matter, we use periastron advance $\dot{\omega}$ of four binary pulsars (PSR B1913+16, PSR B1534+12, PSR J0737-3039 and PSR B2127+11C) to constrain their Yukawa parameters: $\lambda = (3.97 \pm 0.01) \times 10^8 \text{m}$ and $\alpha = (2.40 \pm 0.02) \times 10^{-8}$. It might help us to distinguish different gravity theories and get closer to the new physics.

Keywords. gravitation, relativity, pulsars: PSR B1913+16, PSR B1534+12, PSR J0737-3039, PSR B2127+11C

1. Introduction

The possible gravity-like “fifth” fundamental force in macroscopic scale suggested by Fischbach et al. (1986) evokes interest in many theories which intend to unify gravity with other known forces. The presence of this fifth force could be detected by searching for apparent deviations from Newtonian gravity. For instance, the fifth force would arise from the exchange of a new ultra-light boson which coupled to ordinary matter with a strength comparable to gravity. Typically, through adding a hypothetical Yukawa force to the Newtonian potential, this modified potential per mass takes the form:

$$U(r) = -\frac{GM}{r} \left(1 + \alpha e^{-r/\lambda}\right),$$

where $\alpha$ represents the strength of the Yukawa coupling, and $\lambda$ represents its length scale. Quite a number of works, such as Anderson et al. (1998), Fischbach & Tulmadge (1999), Reynaud & Jaekel (2005), Sealfon et al. (2005), Brownstein & Moffat (2006) and Iorio (2007), have been done to constrain these two parameters in astronomical scales.

Since the discovery of the binary pulsar PSR B1913+16 by Hulse & Taylor (1975), binary pulsars promise an unprecedented opportunity to measure the effects of relativistic gravitation – see Stairs (2004), Lorimer (2005) for a review. For example, pulsar timing has provided indirect evidence for the existence of gravitational waves (Detweiler 1979), the binary pulsars data can constrain the existence of massive black hole binaries (Lommen & Backer 2001), and the binary pulsars can also test the effects of strong relativistic internal gravitational fields on orbital dynamics (Bell et al. 1996). In addition, binary pulsars could help us to test various gravity theories. By fitting the arrival time of pulsars, observational parameters of binary pulsar are obtained in high precision. It worthy of noted that the periastron advance for binary pulsars could reach several degrees per
year, which is about $10^5$ more than the perihelion advance of Mercury. Hence, the relativistic effects from binary pulsar are more remarkable than other celestial systems. In this paper we chose four best studied pulsar binaries: PSR B1913+16, PSR B1534+12, PSR J0737-3039, and PSR B2127+11C. We mainly focus on $\dot{\omega}$ of these four binaries data to constrain the Yukawa parameters.

2. Secular periastron precession with fifth force

When we consider only two body ($M_1$ and $M_2$), the equations of motion of a point-mass binary with fifth force up to first order post-Newtonian approximation yields

$$\ddot{\mathbf{r}} = \mathbf{a}_N + \mathbf{a}_{1PN},$$

where

$$\mathbf{a}_N = -\frac{GM}{r^2} \left[ 1 + \alpha \left( 1 + \frac{r}{\lambda} \right) \exp\left( -\frac{r}{\lambda} \right) \right] \mathbf{n},$$

$$\mathbf{a}_{1PN} = -\frac{GM}{c^2 r^2} \left[ \left( \gamma + 3 \nu \right) v^2 - 2 \left( \gamma + \beta + \nu \right) \frac{GM}{r} - \frac{3}{2} \nu \dot{v} \right] \mathbf{n} - 2 \left( 1 + \gamma - \nu \right) \dot{r} \mathbf{v},$$

where $M = M_1 + M_2$, $\dot{r} = \dot{n}_{12}$, $\mathbf{v} = \mathbf{v}_1 - \mathbf{v}_2$, $\nu = M_1 M_2 / M^2$, $r = r_{12}$, $\mathbf{n} = \mathbf{n}_{12}$ and $a = \frac{d\mathbf{v}_{12}}{dt}$. By the aid of the averaging method (Kozai, 1959), the secular periastron advance for a binary pulsar in 1PN is

$$\frac{d\omega}{dt} = \frac{1}{2} \frac{n \alpha p^2}{\lambda^2} e^{-p/\lambda} + (2 + 2\gamma - \beta) \frac{GMn}{c^2 p},$$

where $n^2 a^3 = GM$, $p = a(1 - e^2)$, $a$ is the semi-major axis and $e$ is the eccentricity of the binary. The periastron shift caused by Yukawa force is

$$\left. \frac{d\omega}{dt} \right|_{\text{Yukawa}} = \frac{1}{2} \frac{n \alpha p^2}{\lambda^2} e^{-p/\lambda},$$

which is different from the result given by (Iorio 2008). In this paper, we keep the angular momentum in the process of using the averaging method instead of approximate treatments such as $\exp(-r/\lambda) \approx 1 - r/\lambda$ (Iorio 2008) to calculate $\dot{\omega}$.

3. Constraints on the Yukawa parameters

Based on the same method of Damour & Esposito-Farèse (1996), we will constrain the Yukawa parameters in 1σ confidence level. Each set of binary data leads to a reduced $\chi^2$:

$$\chi^2_{\text{binary}}(\alpha, \lambda) = (\dot{\omega}_{\text{theory}} - \dot{\omega}_{\text{obs}})^2 / \sigma_{\text{obs}}^2.$$  

To combine the constraints on $\alpha$ and $\lambda$ coming from different double pulsars systems, we add their individual $\chi^2$ as if they were part of a total experiment with uncorrelated Gaussian errors:

$$\chi^2_{\text{total}}(\alpha, \lambda) = \chi^2_{1913+16}(\alpha, \lambda) + \chi^2_{1534+12}(\alpha, \lambda) + \chi^2_{0737-3039}(\alpha, \lambda) + \chi^2_{2127+11C}(\alpha, \lambda).$$

Therefore, the contour level $\Delta \chi^2_{\text{total}}(\alpha, \lambda) = 2.3$, $\Delta \chi^2_{\text{total}}(\alpha, \lambda) = 6.17$, and $\Delta \chi^2_{\text{total}}(\alpha, \lambda) = 11.8$, where $\Delta \chi^2_{\text{total}}(\alpha, \lambda) = \chi^2_{\text{total}}(\alpha, \lambda) - (\chi^2_{\text{total}}(\alpha, \lambda))_{\text{min}}$, define respectively for two degrees of freedom the 68.3%, 95.4% and 99.73% confidence levels. The 1σ fit values for the Yukawa parameters are $\lambda = (3.97 \pm 0.01) \times 10^8$ m and $\alpha = (2.40 \pm 0.02) \times 10^{-9}$ with $\chi^2_{\text{min}} = 21.47$. 
4. Conclusions

In this work, we use 4 double pulsars data (PSR B1913+16, PSR B1534+12, PSR J0737-3039, PSR B2127+11C) to constrain the Yukawa parameters and obtain $\lambda = (3.97 \pm 0.01) \times 10^8$ m and $\alpha = (2.40 \pm 0.02) \times 10^{-8}$ at 1$\sigma$ level. It demonstrates double pulsars could be a good test-bed for testing gravitational theories.

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SPAN512: A new mid-latitude pulsar survey with the Nançay Radio Telescope

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Abstract.
We present an ongoing survey with the Nançay Radio Telescope at L-band. The targeted area is 74° ≤ l < 150° and 3.5° < |b| < 5°. This survey is characterized by a long integration time (18 min), large bandwidth (512 MHz) and high time and frequency resolution (64 µs and 0.5 MHz) giving a nominal sensitivity limit of 0.055 mJy for long period pulsars. This is about 2 times better than the mid-latitude HTRU survey, and is designed to be complementary with current large scale surveys. This survey will be more sensitive to transients (RRATs, intermittent pulsars), distant and faint millisecond pulsars as well as scintillating sources (or any other kind of radio faint sources) than all previous short-integration surveys.

Keywords. surveys, pulsars: general

5. Introduction
Major high-sensitivity pulsar surveys have recently started at different radio observatories due to improvement of digital backends and computing resources over the past few years. These L-Band surveys, ie. PALFA (Cordes et al. 2006), HTRU North (Barr 2011) and South (Keith et al. 2010), are concentrating their efforts at low galactic latitude (|b| ≤ 3.5°). We present here a new survey with the Nançay Radio Telescope (NRT) at intermediate latitude outside the PALFA sky that started early 2012 and designed to be more sensitive than the HTRU mid-latitude survey.

6. Observations
Observations are made with the new state-of-the-art NUPPI backend based on a CASPER† Roach board. Compared to the previous BON instrument used for past surveys (e.g. Cognard et al. 2011 and Guillemot et al. 2012) the bandwidth is increased by a factor of 4. Also this versatile backend now performs a full Polyphase Filter Bank to mitigate the frequency leakage of RFIs.

The targeted field of view (74° ≤ l < 150° and 3.5° < |b| < 5° for 230 square degrees) consists of a grid of ~ 5800 18-min pointings recorded with a 64 µs time resolution with

† https://casper.berkeley.edu/
Figure 1. Left panel: View of the Galactic Plane in galactic coordinates. The two black boxes delimit the SPAN512 area and the black dots represent the 859 pointings made to date. The dashed line shows the Arecibo North declination limit. Right panel: View of the Galactic Plane from the North Galactic Pole. The Galactic Center is located at (0,0). The gray scale is computed from the NE 2001 electron density model by Cordes & Lazio (2002).

Table 1. Parameters of the SPAN survey

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling time</td>
<td>64 µs</td>
</tr>
<tr>
<td>Total bandwidth</td>
<td>512 MHz</td>
</tr>
<tr>
<td>Number of channels</td>
<td>1024</td>
</tr>
<tr>
<td>Center frequency</td>
<td>1486 MHz</td>
</tr>
<tr>
<td>Integration time</td>
<td>18 min</td>
</tr>
<tr>
<td>Final quantization</td>
<td>4 bits</td>
</tr>
<tr>
<td>Gain</td>
<td>1.4 K/Jy</td>
</tr>
<tr>
<td>System temperature</td>
<td>35 K</td>
</tr>
<tr>
<td>Nominal sensitivity</td>
<td>0.055 mJy</td>
</tr>
<tr>
<td>Total observing time</td>
<td>1740 hours</td>
</tr>
</tbody>
</table>

1024 channels over the 512 MHz bandwidth. Given the NRT system temperature and gain, we estimate the minimum flux density for long period pulsars to be 55-70 µJy depending on the pointing declination. The basic parameters of the survey are listed in Table 1.

7. Processing

A total data volume of 50 TB is expected after completion of this program. To search these data, 2 different schemes are considered, both using the Presto† package:

- A quicklook pipeline that reduces the original time resolution by a factor of 4 is used on site and is able to keep up with the data acquisition. No acceleration search is performed at this stage.
- To search the full-resolution data with acceleration, we are currently implementing a new pipeline‡ to run at the IN2P3 Computing Center¶ developed originally for the ongoing PALFA survey. To remain sensitive to very short orbital period binaries, we also split the observations in half and analyze each separately before combining results. In the light of the recent discoveries of highly dispersed radio bursts (Lorimer et al. 2007

† https://github.com/scottransom/presto
‡ https://github.com/plazar/pipeline2.0
¶ http://cc.in2p3.fr/
and Keane et al. 2012), the data are searched for single pulses up to a DM of 1800 cm$^{-3}$ pc.

8. Conclusion

Preliminary results of the quicklook pipeline indicate a relatively low RFI environment (∼10% of the radio band being masked), especially considering the very wide bandwidth. In the observations to date, three previously known pulsars (including one MSP) were redetected.

About 860 of the 5800 planned pointings have been made (15% of the 230 square degrees of this survey) and completion is expected by 2013 with the discovery of 10 to 30 new sources according to population models (Lorimer et al. 2006).

Acknowledgements

The Nançay Radio Telescope is part of the Paris Observatory, associated with the Centre National de la Recherche Scientifique (CNRS) and the University of Orléans, France. We also acknowledge the Centre de Calcul CC-IN2P3 (IN2P3, CNRS Villeurbanne, France) for providing us with computing resources.

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Annular gap model for multi-wavelength pulsed emission from young and millisecond pulsars

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Abstract. The multi-wavelength pulsed emission from young pulsars and millisecond pulsars can be well modeled with the single-pole 3-dimension annular gap and core gap model. To distinguish our single magnetic pole model from two-pole models (e.g. outer gap model and two-pole caustic model), the convincing values of the magnetic inclination angle and the viewing angle will play a key role.

Keywords. gamma rays: stars, pulsars: general, radiation mechanisms: non-thermal

1. Introduction

Pulsars are fascinating astronomical objects in the universe. Many pulsars, including young normal pulsars and millisecond pulsars (MSPs), radiate multi-wavelength pulsed emission, which have not been completely understood.

High energy emission (e.g. $\gamma$-ray emission) from pulsars takes away a significant fraction of the rotational energy. Thanks to the launching of Astro-rivelatore Gamma a Immagini LEggero (AGILE) and the Fermi Gamma-ray Space Telescope (FGST), more than one hundred new $\gamma$-ray pulsars have been discovered in the last year, including gamma-ray only pulsars and a new population of millisecond pulsars (Abdo et al. 2009, Abdo et al. 2010a, Pellizzoni et al. 2009). From observations, MSPs are analogous to young pulsars, which have multi-wavelength pulsed emission from radio (10$^{-6}$ eV) to $\gamma$-ray band. Do MSPs and young pulsars share a simple model that contains similar emission region and acceleration mechanism to self-consistently explain their multi-wavelength emission?

Some models have been proposed to explain pulsar’s multi-wavelength emission, as we will summarize below, differing on the acceleration region of the primary particles and the mechanism for the production of the high energy photons. Initially aiming to explain the high-energy pulsed emission from young pulsars, four traditional physical or geometrical magnetospheric models which have been proposed to explain pulsed $\gamma$-ray emission of pulsars: the polar cap model (Daugherty & Harding 1994), the outer gap model (Cheng, Ho & Ruderman 1986), TPC/slot gap model (Dyks & Rudak 2003). The distinguishing features of these pulsar models are different acceleration electric field regions for primary particles and relevant emission mechanisms to radiate high energy photons (Du et al. 2011, 2012). One of the key discrepancies of these emission models is the one-pole or two-pole emission pattern with two important geometry parameters: the magnetic inclination angle $\alpha$ and the view angle $\zeta$.

The annular gap model was originally proposed by Qiao et al. (2004, 2007). The critical
field lines divide the polar-cap region of a pulsar magnetosphere into two distinct parts: the core gap region and the annular gap region (Du et al. 2011, 2012). The former gap is located around the magnetic axis and within the critical field lines; the latter is located between the critical field lines and the last open field lines. The width of the annular gap region is anti-correlated with the pulsar period, it is therefore larger for pulsars with smaller spin periods (Du et al. 2010). The region for high energy emission in the annular gap model is concentrated in the vicinity of the null charge surface, i.e., an intermediate emission height, different from the outer gap model. The annular gap has a sufficient
thickness of trans-field lines and a wide altitude range for particle acceleration. This model combines the advantages of the polar gap, the slot gap and the outer gap models, and works well for pulsars with short spin periods. It is a promising model to explain high energy emission from young and millisecond pulsars.

2. Modeled Results of Pulse Profiles and Spectra

A convincing model should have a simple clear emission geometric picture with reasonable input parameters, which can not only reproduce multi-wavelength light curves for young pulsars but also for MSPs. Here we will briefly introduce our modeled results of pulse profiles and phase-averaged spectrum for the Vela pulsar, Crab pulsar and some millisecond pulsars. The detailed calculations in the annular gap model can be found in Du et al. (2010, 2011, 2012).

We can solve the problems of the third peak (P3) in the $\gamma$-ray pulse profiles and the emission mechanism of GeV band for the Vela pulsar (Du et al. 2011; as shown in bottom panel of Figure 1). The GeV band emission from the Vela pulsar is originated mainly from Synchro-curvature radiation (Zhang & Cheng 1995) from primary particles, while synchrotron radiation from secondary particles have some contributions to the low-energy $\gamma$-ray band (e.g., $0.1 - 0.3$ GeV). Meanwhile, the total spectrum (thick black solid line in top panel of Figure 1) is calculated in the annular gap model. It is found that the curvature radiation and synchrotron radiation from primary particles is mainly contributed to $\gamma$-ray band (20 MeV to 20 GeV); synchrotron radiation from CR-induced pairs and ICS-induced pairs dominates the X-ray band and soft $\gamma$-ray band (100 eV to 10 MeV). ICS from the pairs contributes to hard TeV $\gamma$-ray band ($\sim 20$ GeV to 400 GeV).

3. Conclusion

The annular gap model is a self-consistent single-pole model not only for young pulsars (Du et al. 2011, 2012), but also for MSPs (Du et al. submitted). Multi-wavelength pulsed emission can be well explained by this model.

References

Characterizing glitches and timing irregularities in pulsars and magnetars

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Abstract. As the quantity and quality of timing data improves, we have reached the point at which the difference between timing noise and small glitches is unclear. As a consequence, the number of events reported as glitches which show unusual properties, quite different to those of giant glitches, has increased. For example, there is now a substantial population of glitches that apparently involve a decrease in spin-down rate rather than an increase. Motivated by the theoretical implications of such a result, we are conducting a detailed review of how glitches are detected and characterised. We have focused on three main questions: the observational biases affecting glitch detection; the methods used to characterise error bars on changes in spin and spin derivatives; and the physical mechanisms that could potentially explain the different populations of timing irregularities, in the light of improved characterisation. While glitches are thought to be a consequence of the internal dynamics of the star, magnetospheric processes may be responsible for other irregularities, as timing noise and peculiar glitch recoveries. We report the first results from this study, using a small sample of radio pulsars that exhibit a wide variety of glitching behaviour.
Can we see pulsars around Sgr A*?
The latest searches with the Effelsberg telescope.

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Abstract. Radio pulsars in relativistic binary systems are unique tools to study the curved
space-time around massive compact objects. The discovery of a pulsar closely orbiting the super-
massive black hole at the centre of our Galaxy, Sgr A*, would provide a superb test-bed for
gravitational physics. To date, the absence of any radio pulsar discoveries within a few arc
minutes of Sgr A* has been explained by one principal factor: extreme scattering of radio waves
caused by inhomogeneities in the ionized component of the interstellar medium in the central
100 pc around Sgr A*. Scattering, which causes temporal broadening of pulses, can only be
mitigated by observing at higher frequencies. Here we describe recent searches of the Galactic
centre region performed at a frequency of 18.95 GHz with the Effelsberg radio telescope.

Keywords. Pulsars, Sgr A*.

1. Introduction

Both theoretical predictions and observational evidence have shown that a large pop-
ulation of pulsars should exist in the Galactic centre (GC) (e.g. Pfahl & Loeb 2004,
Deneva et al. 2009, Wharton et al. 2012). The discovery of a pulsar closely orbiting (or-
bital period ≤ 1 yr) the supermassive black hole at the centre of our Galaxy, Sgr A*,
would supersede all previous strong field tests of General Relativity (e.g. Wex & Kopeikin
1999, Liu et al. 2012). Despite many radio pulsar searches that have covered the GC re-
gion, a remarkable lack of pulsars have been discovered within the central 100 pc. The
lack of pulsar detections is thought to be caused by extreme scattering of radio waves due
to inhomogeneities in the ionized component of the interstellar medium within 100 pc
of Sgr A* (Lazio & Cordes 1998). Scattering causes temporal broadening of pulses that
has a strong dependence on observing frequency, ν (∝ ν^−4), rendering pulsar periodicity
searches at typical observing frequencies ineffective e.g. the broadening time is expected
to be ~ 500 seconds at 1.4 GHz; 1000 times the length of a typical pulsar period! Unlike
pulse dispersion, which can be corrected for by the use of filterbanks, scatter broadening
cannot be compensated by instrumental means. As such, pulsar searches covering the GC
have been performed at increasingly high frequencies (e.g. Johnston et al. 1995, Kramer

† This work was based on observations with the 100-m telescope of the MPIfR (Max-Planck-
-Institut für Radioastronomie) at Effelsberg. http://www.mpifr-bonn.mpg.de/effelsberg
Can we see pulsars around Sgr A*?

2. Observations and data analysis

From Effelsberg the Sgr A* region is visible at low elevation for approximately 2 hours and 25 minutes everyday. For this reason we have opted to make repeated observations and incoherently combine the data to improve sensitivity. Observations are made using the Effelsberg K-band (18-26 GHz) primary focus receiver and the new XFFTS digital spectrometer operating in pulsar search mode. Using XFFTS we record dual polarizations for 256 spectral channels across a bandwidth of 2 GHz. A test observation of PSR B2020+28 using our observing system can be seen in Figure 1.

Data combination is performed by summing the fluctuation spectra of the dedispersed time series from successive GC observations. So called ‘stack searches’ have been used to find isolated millisecond pulsars in the globular cluster Terzan 5 (Sulman et al. 2006) and to perform efficient acceleration searches on the Parkes multi-beam pulsar survey data (Faulkner et al. 2004). We have investigated the sensitivity of a GC pulsar stack search at Effelsberg by considering the following: assuming the GC pulsars have the same properties as the current known population of disk pulsars we have derived their expected flux density at 18.95 GHz assuming an average spectral index of $-1.8$ and placed at the distance of the GC. From these values the expected detection signal-to-noise ratio (S/N) has been calculated for a single 2 hour 25 minute observation. Figure 2 shows the results of this analysis. From statistical considerations the detection threshold of this search corresponds to a $S/N \sim 10$. It can be seen that a number of pulsars would already be possible to detect with a single observation at 18.95 GHz. The number of pulsars possible to detect increases as more observations are combined.

3. Results and future work

To date 14 successful observations of the GC region have been performed. Each observation has been independently searched for periodic and impulsive signals in addition to a search of the combination of all 14 observations. In the data taken so far no pulsars have been detected. Assuming minimal atmospheric contributions to the system temperature
Figure 2. Expected detection S/N after a single 18.95 GHz observation at Effelsberg plotted against the predicted flux densities of the known pulsar population placed at the distance of the GC. The dotted horizontal lines indicate the minimum number of combined observations required to make a detection above our threshold of \( S/N \sim 10 \). The red line shows our current sensitivity limit based on a combination of 14 GC observations.

we can place upper limits on the flux density of normal pulsars (10% duty cycle) within 1.7 pc of Sgr A* at the observing frequency of 18.95 GHz:

\[
S/N \sim 10 \quad \text{flux density limit of individual observations:} \quad \sim 24 \, \mu\text{Jy}
\]

\[
S/N \sim 10 \quad \text{flux density limit of 14 stacked observations:} \quad \sim 12 \, \mu\text{Jy}
\]

We will continue observations of the Sgr A* region since the emission beams of pulsars in close orbits could precess into the line-of-sight on the timescale of years (e.g. Macquart et al. 2010). For the target pulsars our stacking algorithm poses a problem. Such pulsars may have significant line-of-sight acceleration as they move in the gravitational potential of Sgr A* and thus would show Doppler changes in their pulse frequency. After data combination, Doppler shifts could smear the signal and reduce the spectral S/N. To counteract Doppler effects caused by orbital motion we are investigating ‘stack-slide searches’ where the spectra are added with different trial frequency offsets.

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A survey of nulling pulsars using the Giant Meterwave Radio Telescope

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Abstract.
Several pulsars show sudden cessation of pulsed emission, which is known as pulsar nulling. In this paper, the nulling behaviour of 15 pulsars is presented. The nulling fraction of these pulsars, along with the degree of reduction in the pulse energy during the null phase are reported for these pulsars. A unique nulling behaviour is reported for PSR J1738-2330, which also showed quasiperiodic bursts. The distributions of lengths of the null and burst phases as well as the typical nulling time scales are estimated for eight strong pulsars. A comparison of the nulling time scales of four pulsars with similar nulling fraction suggests that the fraction of null pulses probably does not quantify the nulling behaviour of a pulsar in full detail. Analysis of these distributions also indicate that while the null and the burst pulses occur in groups, the transition from the null to burst phase and vice versa can be modeled by a Poisson point process.
The surface and inner temperatures of magnetars

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Abstract. Assuming that the timescale of the magnetic field decay is approximately equal to that of the stellar cooling via neutrino emission, we obtain a one-to-one relationship between the effective surface thermal temperature and the inner temperature. The ratio of the effective neutrino luminosity to the effective X-ray luminosity decreases with decaying magnetic field.

Keywords. Magnetar, neutrino luminosity, surface thermal temperature, inner temperature.

1. Introduction

Magnetars are ultra-magnetized neutron stars (NSs) with magnetic fields largely in excess of the quantum critical field. The majority of magnetars are classified into two populations: the soft gamma-ray repeaters (SGRs), and the anomalous X-ray pulsars (AXPs). Pulsars have been recognized to be normal neutron stars, but sometimes have been argued to be quark stars (e.g., Xu 2005; Du et al. 2009). After their formation, magnetars cool much more efficiently by interior neutrino emission than by surface photon emission. The neutrino emission mechanisms in the stellar cores may be divided into two groups, which leads to standard or rapid cooling. The standard cooling goes mainly via the modified Urca process and the nucleon-nucleon bremsstrahlung process (e.g., Yakovlev & Pethick 2004), whereas rapid cooling is strongly enhanced by the direct Urca process.

In this paper, we focus on the non-thermal neutrino energy losses in the cores which control cooling of young and middle age \((t \lesssim 10^4 \text{ yrs}, \text{ and } B \sim 10^{14} - 10^{15} \text{ G})\) magnetars. In our model, for simplicity, we restrict ourselves by consideration of magnetars whose cores contain the standard composition of dense matter (neutrons, with some admixtures of protons and electrons). In the central region of a magnetar, the electron capture process is expected to occur because of high value of the electron Fermi energy (e.g., Gao et al. 2011a; Gao et al. 2011b). We calculate the effective neutrino luminosity, and simulate numerically the relationship between the surface thermal temperature and the inner temperature of a magnetar.

2. Surface temperatures of magnetars

In this section, what we care about is the effective soft X-ray/gamma-ray luminosity \(L_{\gammaX}^{\text{eff}}\) and the effective surface temperature \(T_{\text{suf}}^{\text{eff}}\) of a magnetar. These two qualities are measured in a local magnetar reference frame. The effective surface temperature is defined by the Stefan law,

\[
L_{\gammaX}^{\text{eff}} \approx L_{X}^{\text{eff}} = 4\pi R^2 \sigma (T_{\text{suf}}^{\text{eff}})^4,
\]

(2.1)
where $R$ is the circumferential stellar radius, $\sigma$ is the Stefan-Boltzmann constant, and $L_{\text{eff}}^s$ is the thermal surface luminosity in a local magnetar reference frame. By using Eq. 1, we plot the diagram of $\log T_{\text{eff}}^s$ vs. $\log B$, as shown in Fig. 1.

3. Inner temperatures of magnetars

According to our magnetar model, we can compute the effective neutrino luminosity of a magnetar as follows:

$$L_{\nu}^{\text{eff}} = \Lambda(B,T) V(3P_2) \times \frac{(2\pi)^3}{hV_1} G_F C^2 \gamma (1 + 3a^2)$$

$$\times \int d^3n_e d^3n_p d^3n_n d^3n_\nu \delta(E_\nu + Q - E_e) \delta^3(\vec{K}_f - \vec{K}_i) S(E_\nu),$$

(3.1)

where $\Lambda(B,T)$ is the ‘Landau level-superfluid modified factor’, $S = f_e f_p (1 - f_n)(1 - f_\nu)$ ($f(j)$ is the fraction of phase space occupied at energy $E_j$), and the rest terms are defined in our recent papers (e.g., Gao et al. 2011a; Gao et al. 2011b; Gao et al. 2012a; Gao et al. 2012b). We calculate the ratios of $L_{\nu}^{\text{eff}} / L_X^{\text{eff}}$ (or $L_\nu^{\infty} / L_X^{\infty}$) in different intense fields. The main results are presented as follows: When the magnetic field $B \sim (3.0 \times 10^{15} - 2.0 \times 10^{14})$ G, accordingly, $L_{\nu}^{\text{eff}} / L_X^{\text{eff}}$ (or $L_\nu^{\infty} / L_X^{\infty}$) $\sim 22.93 \sim 1.61$. The details can be seen in Fig. 2. Assuming that the timescale of the magnetic field decay is equal to the timescale of stellar cooling via neutrino emission, we obtain a one-to-one relationship between $T_{\text{eff}}^s$ and $T_{\text{int}}$, as shown in Fig. 2.

4. Conclusions

Calculations show that $T_{\text{int}}$ is 1-2 orders of magnitude higher than $T_{\text{eff}}^s$, and the ratio of the magnetar neutrino luminosity to the magnetar soft X-ray luminosity, decreases with decaying magnetic field.
Figure 2. The schematic diagram of $L_\nu^{\text{eff}}/L_X^{\text{eff}}$ (or $L_\nu^{\infty}/L_X^{\infty}$) as a function of $B$.

Figure 3. The schematic diagrams of $T_{\text{eff}}^{\text{int}}$ vs. $T_{\text{eff}}^{\text{suf}}$. The range of $T_{\text{eff}}^{\text{suf}}$ is assumed to be $(1.835 \times 10^7 \sim 1.180 \times 10^7)$ K arbitrarily, corresponding to $B \sim (3.0 \times 10^{15} \sim 1.6 \times 10^{14})$ G. Dot-dashed line, dotted line and dashed line are for the initial value of $T_{\text{eff}}^{\text{int}} = 2.70 \times 10^8$ K, $2.60 \times 10^8$ K and $2.50 \times 10^8$ K, respectively.

5. Acknowledgements

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References

Chandra observations of black widow pulsars

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Abstract. We describe the first X-ray observations of binary millisecond pulsars PSR J0023+0923, J1810+1744, J2215+5135, and J2256−1024. All are Fermi gamma-ray sources and three are 'black-widow' pulsars, with companions of mass < 0.1 M⊙. Data were taken using the Chandra X-Ray Observatory and covered a full binary orbit for each pulsar. PSRs J2215+5135 and J2256−1024, show significant orbital variability and X-ray flux minima coinciding with eclipses seen at radio wavelengths. This is consistent with intrabinary shock emission characteristic of black-widow pulsars. The other two pulsars, PSRs J0023+0923 and J1810+1744, do not demonstrate significant variability, but are fainter than the other two sources. Spectral fits yield power-law indices that range from 1.4 to 2.3 and blackbody temperatures in the hundreds of eV. The spectrum for PSR J2215+5135 shows a significant hard X-ray component (41% of counts are above 2 keV), which is additional evidence for the presence of intrabinary shock emission.

Keywords. pulsars: general, X-rays: binaries

1. Introduction

Of the roughly 2000 radio pulsars known today, about 10% are millisecond pulsars (MSPs), old neutron stars which have been spun up, through accretion of material from a companion. Many details of this recycling process remain unknown, but it is clear that most known MSPs have degenerate white dwarf companions with masses between 0.1 and 0.4 M⊙. However, some (up to 25%) of MSPs are isolated. The process through which these MSPs were formed is unclear. One attractive theory is that the companions of isolated MSPs were ablated through energetic particles, X-rays, and/or gamma-rays produced in the intrabinary shock between the pulsar wind and that of the companion.

The first pulsar showing evidence for the ablation process was the black-widow pulsar PSR B1957+20, which has an extremely low mass companion (0.020 M⊙), shows radio eclipses due to absorption in the wind of the companion and dramatic pulse delays around the time of eclipse due to propagation through the wind. A 2002 ACIS-S observation (OBSID 1911) revealed unresolved synchrotron emission that is modulated throughout the orbit, with roughly half of the emission due to the interaction of the pulsar and stellar...
Figure 1. Lightcurves for the four observed MSPs. Each bin corresponds to one tenth of an observation, and the dotted lines correspond to radio eclipse times. PSR J0023+0923 does not show a radio eclipse. Note the absence of photons (specifically hard photons) during the radio eclipses of both PSRs J2215+5135 and J2256−1024.

winds and half from the pulsar itself. This observation showed a dip in the lightcurve no wider than one tenth of an orbit at an orbital phase of 0.25 (Stappers et al. 2003).

The body of knowledge regarding black-widow pulsars is still lacking. We present analysis of rare observations of four pulsars with low mass companions, each observed for approximately one orbit.

2. Observations and analysis

We observed PSRs J0023+0923, J1810+1744, J2215+5135, and J2256−1024 for 15 ks, 22 ks, 19 ks, and 22 ks respectively (Fig. 1). The data were taken using Chandra’s ACIS-S mode and analyzed using Chandra’s data analysis suite, CIAO (version 4.2).
Table 1. Timing and X-ray properties of four Fermi-associated radio MSPs. Timing properties are from 350-MHz observations with the Green Bank Telescope (Bangale et al. 2010). PSR J0023+0923 was fit with both a blackbody model and a power law model (separately), while PSR J2256–1024 was fit with a combined blackbody and power law model. PSR B1957+20 is shown for comparison.

Lightcurves were determined for each source using counts in the 0.2 keV to 8 keV range, as Chandra has very little effective area outside of that range. The number of counts detected for each source ranged from 43 to 141 (Table 1). Each lightcurve was binned such that each bin represents one tenth of the observation. These lightcurves were then compared to uniform distributions using the $\chi^2$ test and Kolmogorov-Smirnov test (Kolmogorov 1933) to determine their orbital variability.

Spectra were then analyzed using Chandra’s spectral fitting platform, Sherpa. The data were then fitted over energies between 0.2 keV and 8 keV. Because of the small number of counts, we fixed $N_H$ at a constant value (with 10 free electrons per neutral Hydrogen) in all of the fits. Although in reality, the spectra for all of the sources will likely contain a blackbody component and a power-law component, we were not able to fit both of these components for PSRs J0023+0923, J1810+1744, and J2215+5135. Therefore, we provide the results of single-component fits for these pulsars. These fits are consistent with intrabinary shock emission, however, additional observations are necessary to constrain both model components, as well as model the orbital geometry of these binary systems.

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Spin rotation, Chandler wobble and free core nutation of isolated multi-layer pulsars

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Abstract.
At present time there are investigations of precession and nutation for very different celestial multi-layer bodies: the Earth (Getino 1995), Moon (Gusev 2010), planets of Solar system (Gusev 2010) and pulsars (Link et al. 2007). The long-periodic precession phenomenon was detected for few pulsars: PSR B1828-11, PSR B1557-50, PSR 2217+47, PSR 0531+21, PSR B0833-45, and PSR B1642-03. Stairs, Lyne & Shemar (2000) have found that the arrival-time residuals from PSR B1828-11 vary periodically with a different periods. According to our model, the neutron star has the rigid crust (RC), the fluid outer core (FOC) and the solid inner core (SIC). The model explains generation of four modes in the rotation of the pulsar: two modes of Chandler wobble (CW, ICW) and two modes connecting with free core nutation (FCN, FICN) (Gusev & Kitiashvili 2008). We are propose the explanation for all harmonics of Time of Arrival (TOA) pulses variations as precession of a neutron star owing to differential rotation of RC, FOC and crystal SIC of the pulsar PSR B1828-11: 250, 500, 1000 days. We used canonical method for interpretation TOA variations by Chandler Wobble (CW) and Free Core Nutation (FCN) of pulsar.

The two-layer model can explain occurrence twin additional fashions in rotation pole motion of a NS: CW and FCN. In the frame of the three-layer model we investigate the free rotation of dynamically-symmetrical PSR by Hamilton methods. Correctly extending theory of SIC-FOC-RC differential rotation for neutron star, we investigated dependence CW, ICW, FCN and FICN periods from flatness of different layers of pulsar.

Our investigation showed that interaction between rigid crust, RIC and LOC can be characterized by four modes of periodic variations of rotation pole: CW, retrograde Free Core Nutation (FCN), prograde Free Inner Core Nutation (FICN) and Inner Core Wobble (ICW). In the frame of the three-layer model we proposed the explanation for all pulse fluctuations by differential rotation crust, outer core and inner core of the neutron star and received estimations of dynamical flattening of the pulsar inner and outer cores, including the heat dissipation. We have offered the realistic model of the dynamical pulsar structure and two explanations of the feature of flattened of the crust, the outer core and the inner core of the pulsar.
Constraints of the compactness of the isolated neutron stars via X-ray phase-resolved spectroscopy

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Abstract. A model with a condensed iron surface and partially ionized hydrogen-thin atmosphere allows us to fit simultaneously the observed general spectral shape and the broad absorption feature (observed at 0.3 keV) in different spin phases of the isolated neutron star RBS 1223. We constrain some physical properties of the X-ray emitting areas, i.e. the temperatures \(T_{pole1} \sim 105\text{ eV}, T_{pole2} \sim 99\text{ eV}\), magnetic field strengths \(B_{pole1} \approx B_{pole2} \approx 8.6 \times 10^{13}\text{ G}\) at the poles, and their distribution parameters (\(a1 \sim 0.61, a2 \sim 0.29\), indicating an absence of strong toroidal magnetic field component). In addition, we are able to place some constraints on the geometry of the emerging X-ray emission and the gravitational redshift \(z \sim 0.16^{+0.03}_{-0.01}\) of the isolated neutron star RBS 1223.

Keywords. stars: neutron, X-rays: stars, techniques: spectroscopic

1. Introduction

Observations and modeling of thermal emission from isolated neutron stars can provide not only information on the physical properties such as the magnetic field, temperature, and chemical composition of the regions where this radiation is produced, but also we may infer on the properties of matter at higher densities deeper inside the star.

In particular, the study of thermal emission from isolated neutron stars may allow one to infer the surface temperature and total flux measured by a distant observer and to estimate the real parameters. With the known distance and the redshifted radius of the neutron star the actual radius and mass of a neutron star are:

\[
R = R^\infty \left[1 - 2GM/Rc^2\right]^{1/2}, \quad M = \frac{c^2}{2G} \left[1 - \left(\frac{R}{R^\infty}\right)^2\right]^{1/2}
\]

(see, e.g. Zavlin (2009)).

The detection and identification of any absorption/emission feature in the spectrum or performing rotational phase-resolved spectroscopy of isolated neutron stars will allow us to determine gravitational redshift and directly estimate the mass-to-radius ratio, \(M/R\). Together they yield a unique solution for \(M\) and \(R\). These spectral features may allow to measure the neutron star magnetic field and provide an important input for modeling of magnetized atmospheres.

RBS 1223 shows the highest pulsed fraction (13-42%, depending on energy band, see Fig. 1) and strongest broad absorption feature (Schwope et al. 2007) of all isolated neutron stars.

High quality rotation phase resolved spectroscopy is needed in order to fit with neutron star magnetized atmosphere models and to constrain the gravitational redshift of the neutron star (Suleimanov et al. 2010; Hambaryan et al. 2011).
2. Data analysis and results

Using the data collected with XMM-Newton EPIC pn from the 12 publicly (similar instrumental setup, i.e. Full Frame, Thin1 Filter) available observations, in total presenting about 175 ks of effective exposure time, we extracted spin-phase resolved spectra with high S/N ratio (Fig. 1) and fitted simultaneously with highly magnetized isolated neutron star surface/atmosphere models (Suleimanov et al. 2010). These models are based on various local models and compute rotational phase dependent integral emergent spectra of isolated neutron star, using analytical approximations.

The basic model includes temperature/magnetic field distributions over isolated neutron star surface†, viewing geometry and gravitational redshift. Three local radiating surface models are also considered, namely, a naked condensed iron surface (van Adelsberg & Lai 2006) and partially ionized hydrogen model atmospheres, semi-infinite or finite atop of the iron condensed surface.

The observed phase resolved spectra (i.e. energy-spin phase image, Fig. 2) of the isolated neutron star RBS 1223 are satisfactorily fitted (verified also via MCMC, Fig. 2) with two slightly different physical and geometrical characteristics of emitting areas, a model parameterized with a Gaussian absorption line superimposed on a blackbody spectrum and by the model of a condensed iron surface, with partially ionized, optically thin hydrogen atmosphere above it, including vacuum polarization effects, as orthogonal rotator. Note, the latter one is more physically motivated. We have additionally performed Markov Chain Monte Carlo (MCMC) fitting as implemented in XSPEC.

The fit also suggests the absence of a strong toroidal magnetic field component. Moreover, the determined mass-radius ratio, \((M/M_{\odot})/(R/\text{km}) = 0.087 \pm 0.004\), suggests a very stiff equation of state of RBS 1223.

† \(T^4 = T_{p1.2}^4 \frac{\cos^2\theta + a_{1.2} \sin^2\theta}{\cos^2\theta + a_{1.2} \sin^2\theta + a_{1.2} \sin^2\theta} + T_{\text{min}}^4, B = B_{p1.2} \sqrt{\cos^2\theta + a_{1.2} \sin^2\theta},\) where the parameters \(a_{1.2}\) are approximately equal to the squared ratio of the magnetic field strength at the equator to the field strength at the pole, \(a_{1.2} \approx (B_{eq}/B_{p1.2})^2\). Using these parameters we can describe various temperature distributions, from strongly peaked \((a \gg 1)\) to the classical dipolar \((a = 1/4)\) and homogeneous \((a = 0)\) ones.
Figure 2. Energy-Phase image of RBS1223 combined from different observations. Rotational phase-folded light curve in the broad energy, 0.2-2.0 keV, band (left panel) and the phase averaged spectrum (bottom panel) are shown.

Figure 3. Probability density distribution of gravitational redshift by Markov Chain Monte Carlo (MCMC) fitting with the model of strongly magnetized neutron star condensed iron surface and partially ionized Hydrogen thin atmosphere atop it (left panel). Dashed vertical lines indicate the highest probability interval (68%). Mass-radius relations (right panel) for several EOS (Haensel et al. (2007), thin solid curves), and a strange star (thin dash-dotted). Thick dashed: curve of constant $R^\infty = R/\sqrt{1 - 2GM/Rc^2} = 17$ km (Trümper (2005)).

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Magnetars are super hot and super cool

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Abstract. We examine to what extent the inferred surface temperature of magnetars in quiescence can constrain the presence of a superfluid in the neutron star core and the role of magnetic field decay in the core. By performing detailed simulations of neutron star cooling, we show that extremely strong heating from field decay in the core cannot produce the high observed surface temperatures nor delay the onset of neutron superfluidity in the core. We find that it is not possible to conclude that magnetar cores are in a non-superfluid state purely from high surface temperatures. We find that neutron superfluidity in the core occurs less than a few hundred years after neutron star formation for core fields \( B < 10^{16} \) G. Thus all known neutron stars, including magnetars, without a core containing exotic particles, should have a core of superfluid neutrons and superconducting protons.

Keywords. dense matter, neutrinos, pulsars: general, stars: evolution, stars: neutron

Anomalous X-ray pulsars and soft gamma-ray repeaters form the magnetar class of neutron stars, i.e., neutron stars which possess superstrong magnetic fields \( (B \gtrsim 10^{14} \text{ G}) \) in most cases. Their strong fields likely power the activity seen in these objects (see Woods & Thompson 2006; Mereghetti 2008, for review). One notable property of magnetars is that their observed surface temperatures in quiescence are significantly higher than those of other neutron stars of a similar age (see Fig. 1). In fact, they are too high for neutron stars that cool passively, i.e., without an additional source of internal heat (accretion heating can be excluded by, e.g., non-detections of binary companion or disk emission). An interesting problem concerns the heat generated from magnetic field decay, which has been proposed to be the source for the high temperatures of magnetars (see, e.g., Thompson & Duncan 1996). This heat can strongly influence the time/age at which the core becomes superfluid if heating/field decay occurs in the core (Thompson & Duncan 1996; Arras et al. 2004; Dall’Osso et al. 2009). The problem is important since the presence of superfluid components has a strong impact on magnetar interior dynamics.

Fig. 2 shows the temperature as a function of density and age for a neutron star cooling model that has no additional sources of internal heat (left panel), core heating due to magnetic field decay (center panel), and crust heating (right panel); see Ho et al. (2012) for details on the heat source. At very early ages, the neutron star core cools so rapidly by neutrino emission that the crust does not have time to react; thus the crust is hotter than the core. A cooling wave travels from the core to the surface, bringing the NS to a relaxed, isothermal state. Depending on the properties of the crust, the relaxation time is \( \sim 10 – 100 \) yr (Lattimer et al. 1994; Gnedin et al. 2001; Yakovlev et al. 2011). The center panel shows that the extra heat generated from magnetic field decay in the core is efficiently removed by neutrino emission; the surface temperatures from this (core heating only) model is too low to explain the observed temperatures of magnetars (see Fig. 1). Meanwhile, the right panel shows that a heat source in the outer crust can
Figure 1. Surface temperature evolution for models with superfluid and crust heating (short-dashed), superfluid and core heating (solid), no superfluid and no heating (dotted), and superfluid and no heating (long-dashed); models with heating have a fully accreted hydrogen envelope (with a $10^{15}$ G radial surface magnetic field), while models with no heating have an iron envelope. Initial core magnetic field = $10^{16}$ G and heating/field-decay time-scale = $10^4$ yr. Data points are magnetars and other neutron stars taken from the McGill SGR/AXP Online Catalog and those listed in Chevalier (2005); Yakovlev et al. (2008); Ho & Heinke (2009); Kaminker et al. (2009), respectively.

very effectively maintain a high temperature near the surface (see Fig. 1) and can power magnetar surface emission (see also Kaminker et al. 2006, 2009).

Fig. 2 also shows the critical temperatures for the onset of superfluidity of core protons in the singlet state ($T_{cp}$), core neutrons in the triplet state ($T_{cnt}$), and crust neutrons in the singlet state ($T_{cns}$); note that the models for the superfluid critical temperature in the core are obtained from fitting the rapid cooling seen in the Cassiopeia A neutron star (Heinke & Ho 2010; Page et al. 2011; Shternin et al. 2011). We can thus see the two main effects of superfluidity on neutron star cooling: slower cooling in the core after protons become superconducting and faster cooling after neutrons become superfluid due to neutrino emission from Cooper pair formation; the latter is strongest in regions near the critical temperature (see Yakovlev & Pethick 2004; Page et al. 2006, for review). It is also evident that most of the core becomes superconducting after $\sim 1$ yr, regardless of the presence of additional heating. For neutrons in the core and heating in the crust, effective thermal decoupling between outer crust and core means that the core cools as if there is no additional source of heat (compare right and left panels of Fig. 2) and the core temperature drops below the critical temperature for neutron superfluidity after a few hundred years. On the other hand, the center panel shows that with extreme core heating (with magnetic field decay time-scale = $10^4$ yr and initial field = $10^{16}$ G), the core temperature stays above $T_{cnt}$ for $\gg 10^2$ yr. However, by more properly accounting for the superconducting state of core protons, the decay time-scale can be $\gg 10^4$ yr (Glampedakis et al. 2011; Ho et al. 2012). This reduces the heating rate, since the rate
is inversely proportional to decay time-scale, and renders core heating ineffective against cooling by strong neutrino emission. As a result, the onset of core neutron superfluidity is not delayed and occurs after a few hundred years. Thus the core of all neutron stars can be treated as being in a superfluid and superconducting state after the neutron star is a few hundred years old. Further details can be found in Ho et al. (2012).

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Birth accelerations of neutron stars

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Abstract. We suggest that neutron stars experienced at birth three related physical changes, which may originate in magneto-rotational instabilities: (i) an increase in period from the initial value $P_0$ to the current value $P_s$, implying a change of rotational energy $\Delta E_{\text{rot}}$; (ii) an exponential decay of its magnetic field from the initial value $B_0$ to the current surface value $B_s$, implying a change of radiative energy $\Delta E_{\text{rad}}$; and (iii) an increase of space velocity from the initial value $v_0$ to the current value $v$, implying a change of kinetic energy $\Delta E_{\text{kin}}$. These changes are assumed to be connected by $\Delta E_{\text{rad}} + \Delta E_{\text{kin}} = \Delta E_{\text{rot}}$. This means that the radiation loss and increase of kinetic energy are both at the expense of a rotational energy loss. It is shown that this energy conversion occurs during times of order of $10^{-4}$ s if the neutron stars are born with magnetic fields in the range of $10^{15} - 10^{16}$ G and initial periods in range 1–20 ms. It is shown that the birth accelerations of neutron stars are of the order of $10^8$ g.

Keywords. Neutron stars

1. Introduction

The idea that neutron stars are born with magnetic fields typical of magnetars ($10^{15} - 10^{16}$ G) and periods typical of millisecond pulsars (1–20 ms) is based on the assumption that neutron stars experienced three related physical processes occurring at the end of their birth. Because of magneto-rotational instabilities occurring in neutron stars during their birth, these stars could experience an abrupt change of rotational energy which could cause a loss of radiative energy and a gain in kinetic energy:

$$\Delta E_{\text{rad}} + \Delta E_{\text{kin}} = \Delta E_{\text{rot}}.$$  \hspace{1cm} (1.1)

A similar energy conversion but with a different radiative term is the basis of the “Rocket Model” proposed by Harrison & Tademaru (1975). The idea of a loss of rotational energy during the birth process of a neutron star was already considered by Usov (1992) for the case of millisecond pulsars. On the other hand, Spruit (2008) has suggested that a differential rotation in the final stages of the core collapse process can produce magnetic fields typical of magnetars. He has pointed out that some form of magneto-rotational instability may be the cause of an exponential growth of the magnetic field; but that once formed in the core collapse, this magnetic field may decay again through magnetic instabilities. In connection with the idea that neutron stars are born as magnetars, Geppert & Rheinhardt (2006) have discussed a magneto-hydrodynamical process that significantly reduces the initial magnetic field of a newly-born neutron star in fractions of a second. According to these authors, such a field reduction is due to magneto-hydrodynamical instabilities, which seem to be inevitable if neutron stars are born as magnetars.

The present work focuses on the initial dynamics of neutron stars. Specifically, by considering Eq. (1.1) and the assumption that neutron stars are born with magnetic fields of magnetars and periods of millisecond pulsars, the birth acceleration of neutron stars will be estimated.
2. The birth-ultrafast magnetic-field-decay model of neutron stars

The Larmor formula for the power radiated by a time-varying magnetic dipole moment \( P = 2\tilde{\mu}^2/(3c^3) \), and the estimate \( \tilde{\mu} \sim \mu_0/\tau^2 \), where \( \tau \) is the characteristic time in the exponential field decay law \( B(t) = B_0e^{-t/\tau} \), imply the equation \( P \approx 2\mu_0^2/(3c^3\tau^4) \), which can be used together with the relation \( \mu_0 = B_0R^3/2 \) to yield the power radiated by a neutron star of radius \( R \) and an initial magnetic field \( B_0 \):

\[
P \approx \frac{B_0^3R^6}{6c^3\tau^4}. \tag{2.1}
\]

Consider now the specific time \( \tau_s \) elapsed during the field decay from the initial value \( B_0 \) to the current surface magnetic field \( B_s \). The condition \( B(\tau_s) = B_s \) and the law \( B(t) = B_0e^{-t/\tau} \) imply \( B_s = B_0e^{-\tau_s/\tau} \) or equivalently

\[
\tau_s = \tau \ln(B_0/B_s). \tag{2.2}
\]

From Eqs. (2.1) and (2.2) it follows that the change of electromagnetic energy radiated \( \Delta E_{\text{rad}} \approx \tau_s P \) is explicitly given by

\[
\Delta E_{\text{rad}} \approx \frac{B_0^3R^6\ln(B_0/B_s)}{6c^3\tau^3}. \tag{2.3}
\]

The initial magnetic field \( B_0 \) is associated with the initial angular frequency \( \Omega_0 \) (or equivalently with its associated initial period \( P_0 \)). The initial rotational kinetic energy of a neutron star is \( I\Omega_0^2/2 \), where \( I = 2MR^2/5 \) is the moment of inertia for a neutron star with mass \( M \). The rotational kinetic energy associated with the surface magnetic field \( B_s \) is \( I\Omega_s^2/2 \), where \( \Omega_s \) is the current angular frequency (and \( P_s \) its associated period) of the neutron star. It is expected that the angular frequency of neutron stars decreases during the field decay of this star. This means that \( \Omega_0 > \Omega_s \) and so the rotational kinetic energy must decrease. Since \( \Omega = 2\pi/P \) it follows that the period increases during the birth process \( (P_s > P_0) \). By assuming that the change of radiative energy in Eq. (2.3) and the change of kinetic energy \( E_{\text{kin}} = Mv^2/2 \) of the neutron star (the initial velocity is taken to be zero) are both at the expense of the change of rotational energy \( \Delta E_{\text{rot}} = 4\pi^2MR^2(P_0^{-2} - P_s^{-2})/5 \) the energy conservation reads

\[
\frac{B_0^3R^6\ln(B_0/B_s)}{6c^3\tau^3} + \frac{1}{2} \frac{Mv^2}{\Delta E_{\text{rot}}} = \frac{1}{5} \left( \frac{1}{P_0^2} - \frac{1}{P_s^2} \right). \tag{2.4}
\]

To get an idea of the order of the time \( \tau \), consider the Crab pulsar B0531+21 which has \( M = 1.4M_\odot \); \( R = 10 \) km; \( P_s = 0.063 \) s; \( B_s = 3.78 \times 10^{12} \) G; \( v_\perp = 141 \) km/s which implies \( v = 172.7 \) km/s, where the relation \( v \approx \sqrt{3/2} v_\perp \) has been used (Lyne & Lorimer 2006). It has been suggested that the Crab pulsar was born with \( P_0 \approx 0.019 \) s (Lyne et al. 1993). Using this initial period and assuming \( B_0 = 5.8 \times 10^{15} \) G, Eq. (2.4) yields \( \tau \approx R/c \). For the magnetar J1809-1943, Eq. (2.4) also implies \( \tau \approx R/c \) if \( P_0 \approx 0.02 \) s and \( B_0 \approx 9.5 \times 10^{15} \) G. For the isolated millisecond pulsar MSP B1257+12, Eq. (2.4) yields \( \tau \approx R/c \) if \( P_0 \approx 0.059 \) s and \( B_0 = 2.7 \times 10^{15} \) G. The time \( \tau = R/c \) agrees with the idea that neutron stars are born with magnetic fields in the range of \( 10^{15}-10^{16} \) G and initial periods in range of 1–20 ms. Magnetic field decays from one to eight orders of magnitude satisfy \( 2.3 \leq \ln(B_0/B_s) \leq 4.4 \). When this relation and \( \tau = R/c \) are used in Eq. (2.2) one has

\[
\tau_s \approx 10^{-4} \text{ s}. \tag{2.5}
\]
This means that the field decay from $B_0$ to $B_s$ is ultrafast if $B_0$ lies in the range of $10^{15} - 10^{16}$ G and $P_0$ in the range of $1 - 20$ ms.

3. Birth accelerations of neutron stars

The energy conversion in Eq. (2.4) occurs suddenly and therefore one can write

$$v \approx a \tau_s, \quad (3.1)$$

where $a$ is the birth acceleration. Equations (2.2), (2.4), (3.1) and $\tau = R/c$ yield

$$a = \sqrt{\frac{8\pi^2c^2(P_0^{-2} - P_s^{-2})}{5 \ln (B_0/B_s)^2} - \frac{B_0^2Rc^3}{3M \ln (B_0/B_s)}}. \quad (3.2)$$

Using this equation with $M = 1.4M_\odot$ and $R = 10$ km, and taking the specific values for $B_s$ and $P_0$ from the ATNF Pulsar Catalogue and assuming values for $P_0$ and $B_0$, the birth acceleration can be calculated and expressed in terms of $g=9.8$ m/s$^2$. Four sets of neutron stars with reported transverse velocities will be now considered:

**Interval: 2 s < $P_s$ ≤ 8.5 s.**

There are 9 neutron stars in this interval. The average values are $P_s = 4.82$ s and $B_s = 3.14 \times 10^{13}$ G. If the values $P_0 = 0.02$ s and $B_0 = 7 \times 10^{15}$ G are assumed then Eq. (3.2) predicts the birth acceleration $a = 5.0 \times 10^8$ g.

**Interval: 1 s ≤ $P_s$ < 2 s.**

There are 29 neutron stars in this interval. The average values are $P_s = 1.32$ s, $B_s = 4.17 \times 10^{12}$ G. If the values $P_0 = 0.02$ s and $B_0 = 5 \times 10^{15}$ G are assumed then Eq. (3.2) gives the birth acceleration $a = 5.8 \times 10^8$ g.

**Interval: 0.02 s ≤ $P_s$ < 1 s.**

There are 130 neutron stars in this interval. The average values are $P_s = 0.41$ s and $B_s = 1.28 \times 10^{12}$ G. If the values $P_0 = 0.02$ s and $B_0 = 5 \times 10^{15}$ G are assumed then Eq. (3.2) implies the birth acceleration $a = 4.5 \times 10^8$ g.

**Interval: 0.0015 s ≤ $P_s$ < 0.009 s.**

There are 9 millisecond pulsars in this interval. The average values are $P_s = 0.005$ s and $B_s = 2.59 \times 10^8$ G. If the values $P_0 = 0.0049$ s and $B_0 = 10^{15}$ G then Eq. (3.2) predicts the birth acceleration $a = 3.1 \times 10^8$ g.

It can be concluded that birth accelerations of neutron stars occur in times $\tau_s \sim 10^{-4}$ s and are of the order of $10^8$ g. If for example, $a = 5 \times 10^8$ g and $\tau_s \sim 10^{-4} s$ are assumed then the birth velocity (kick velocity) is of the order of 500 km/s. This value is approximately the average value for pulsar velocities found by Lyne & Lorimer (2006).

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An XMM-Newton study of the supernova remnant G296.7–0.9

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Abstract. We report on XMM-Newton observations of the Galactic supernova remnant G296.7–0.9. A detailed spectro-imaging X-ray study of G296.7–0.9 was performed. We detected an incomplete shell-like X-ray structure which is located near the boundary of the radio emission at a frequency of 843 MHz. The X-ray spectrum can be best described by an absorbed ionization plasma model accompanied with metallic emission lines, which suggests the plasma is shock heated. No promising compact stellar remnant associated with G296.7–0.9 was found. No Gamma-ray emission of G296.7–0.9 from Fermi-LAT telescope was detected in our study.

Keywords. ISM: supernova remnants, X-rays: individual (G296.7–0.9)

1. Introduction

Supernovae (SNe) and their remnants (SNRs) play a crucial role in the heating and chemical evolution of galaxies. To develop a more general understanding of SN explosions, the interaction between ejected materials and the interstellar medium (ISM), particle acceleration in SNRs, and the effect on their galaxy is indispensable. Until now there are 302 SNRs that have been uncovered in the Milky Way: 274 objects recorded in Green’s catalog (2009) plus 28 objects reported in Ferrand & Safi-Harb (2012). Among those Galactic SNRs, only ~100 of them have been detected in X-rays†. Therefore, to enlarge the sample of X-ray detected SNRs would be valuable.

G296.7–0.9 was initially classified as HII region G296.593–0.975 based on its association with radio recombination lines and an apparently thermal spectrum (Manchester 1969, Caswell & Haynes 1987, Kuchar & Clark 1997, and references therein). However, Schaudel (2003) suggested that G296.7–0.9 is a promising SNR candidate based on its X-ray and radio properties. Its incomplete shell-like morphology and thermal X-ray spectra which can be described well by the Raymond-Smith and the thermal bremsstrahlung models with temperatures of $kT = 0.22 \pm 0.13$ keV and $kT = 0.33 \pm 0.15$ keV provide a strong support for the SNR interpretation. A subsequent multiwavelength study reported by Robbins et al. (2012) confirms that G296.7–0.9 is a Galactic SNR.

In this proceeding, we present a detailed X-ray study of the newly identified Galactic SNR G296.7–0.9 using XMM-Newton observations.

† http://www.physics.umanitoba.ca/snr/SNRcat/
2. Observation & Data Analysis

G296.7–0.9 was observed with XMM-Newton on June 28, 2011 for a ∼13 ks total exposure. In this observation, the EPIC MOS1/2 and PN instruments were operated in full-frame mode using the medium filter to block optical stray light. All the data were processed with the XMM-Newton Science Analysis Software (SAS) package (Version 11.0.0). Calibrated event files for the MOS1, MOS2, and PN detectors were produced using the SAS task `emchain` and `epchain`, following standard procedures. In order to remove the particle contamination and periods of high background, we determined a threshold on the light curve counts and then used the SAS task `tabgtigen` to create the corresponding Good Time Interval (GTI) file. The effective exposure times after background cleaning for MOS1, MOS2, and PN are 4.6 ks, 5.1 ks, and 2.5 ks, respectively.

2.1. Spatial Analysis

Fig. 1 (left panel) displays the merged XMM-Newton MOS1/2 image of G296.7–0.9 in the energy range of 0.5–10.0 keV with 5-ks exposure time overlaid with the Sydney University Molonglo Sky Survey (SUMSS) radio contour at 843 MHz. This image was created by using an adaptive smoothing algorithm with a Gaussian kernel of σ < 3 pixels in order to probe the detailed structure of the diffuse emission. With the better spatial resolution of XMM, an incomplete X-ray shell structure has been revealed. The incomplete X-ray shell-like morphology confirms to an ellipse approximately centered at R.A. = 11\(^{h}\)55\(^{m}\)53\(^{s}\) and DEC = -63\(^{\circ}\)06\(^{\prime}\)25\(^{\prime\prime}\) (J2000). The angular sizes of the semi-major and the semi-minor axes are ∼ 4.7′ and ∼ 3.3′, respectively.

In order to search for the possible stellar remnant associated with G296.7–0.9, we used the SAS task `edetect_chain`. This task runs on the calibrated MOS1/2 and PN image files and invokes several SAS tasks to produce background, sensitivity, and vignetting-corrected exposure maps. In the field of view of the EPIC detectors, 4 sources have been detected. To investigate if these X-ray sources are promising isolated neutron star candidates, we proceeded to search for their possible optical counterparts and calculated the X-ray-to-optical flux ratio \(f_x/f_{opt}\), which provides a rudimentary parameter for discriminating the nature of the source. For an isolated neutron star, \(f_x/f_{opt}\) is typically larger than 1000 (cf. Haberl 2007) while for field stars and active galactic nuclei the

Figure 1. Left: Smoothed XMM-Newton MOS1/2 image of G296.7–0.9 in the energy range of 0.5–10.0 keV with 5-ks exposure time overlaid with the SUMSS radio contour at 843 MHz. The geometrical center inferred from the X-ray morphology is illustrated by the yellow cross. The small cyan circles show the positions of 4 X-ray sources. Right: Energy spectrum of G296.7–0.9 obtained from the XMM-Newton MOS1/2 and PN data was fitted with an absorbed CIE model.
ratio are much lower than the typical < 0.3 and < 50, respectively (Maccacaro et al. 1988; Stocke et al. 1991). Based on the X-ray-to-optical flux ratios, no promising isolated neutron star candidate was found in this study.

2.2. Spectral Analysis

We utilized the XMM-Newton SAS tool `eveselect` to extract the spectrum of G296.7–0.9. The background spectrum was extracted from the nearby source-free elliptical region in the same CCD chip. Response files were constructed by using the XMM-Newton SAS tasks `rmfgen` and `arfgen`. The spectral modeling was performed with the XSPEC software package (version: 12.7.0) using data in the energy band 0.5–10.0 keV.

We examined the spectra with an absorbed collisional ionization equilibrium (CIE) plasma model (XSPEC model: EQUIL) and an absorbed non-equilibrium ionization model of a constant temperature and a single ionization timescale (XSPEC model: NEI). The best-fit CIE model yields a column density of \((1.09 \pm 0.02) \times 10^{22} \text{ cm}^{-2}\) and a plasma temperature of \(kT=0.55^{+0.02}_{-0.01}\) keV (see Fig. 1 right panel). The ionization timescale and the best-fit plasma temperature inferred from the NEI model are \(\tau_{\text{ion}} = (6.63^{+2.95}_{-2.33}) \times 10^{10} \text{ s cm}^{-3}\) and \(kT=0.66 \pm 0.08\) keV. We found the X-ray spectra of G296.7–0.9 can be described similarly well by either a CIE model or a NEI model. No conclusive evidence for the deviation of metal abundances from the solar values was obtained. Emission lines from various metals can be clearly observed (e.g. Mg at \(\sim 1.4\) keV; Si at \(\sim 1.9\) keV). These properties provide a solid evidence for the hot plasma emission from a remnant. And hence the SNR nature of G296.7–0.9 is confirmed.

We further investigated if there is any non-thermal emission in various regions by adding a power-law model on the aforementioned best-fit plasma models. We found that the parameters of the additional power-law cannot be properly constrained. This prompts us to perform the spectral fit with the photon index fixed at the value of \(\Gamma= 2\). No significant improvement of the goodness-of-fit was found.

3. Summary & Conclusion

We have performed a detailed spectro-imaging X-ray study of the supernova remnant G296.7–0.9 with XMM-Newton. An incomplete shell-like X-ray structure, which is well correlated with a radio contour, has been revealed. Its X-ray spectrum is thermal dominated and has shown the presence of a hot plasma which has been heated up by shock waves to a temperature of \(\sim 6 \times 10^6\) K and is accompanied with metallic emission lines. All these observational evidences clearly suggest that G296.7–0.9 is a SNR belong to a shell-like category, confirming the previous results reported by Robbins et al. (2012).

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X-ray studies of the black widow pulsar PSR B1957+20

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Abstract. We report on Chandra observations of the black widow pulsar, PSR B1957+20. Evidence for a binary-phase dependence of the X-ray emission from the pulsar is found with a deep observation. The binary-phase resolved spectral analysis reveals non-thermal X-ray emission of PSR B1957+20, confirming the results of previous studies. This suggests that the X-rays are mostly due to intra-binary shock emission which is strongest when the pulsar wind interacts with the ablated material from the companion star. The geometry of the peak emission is determined in our study. The marginal softening of the spectrum of the non-thermal X-ray tail may indicate that particles injected at the termination shock is dominated by synchrotron cooling.

Keywords. binaries: eclipsing, pulsars: individual (PSR B1957+20)

1. Introduction

The widely accepted scenario for the formation of a millisecond pulsar (MSP) is that an old neutron star has been spun up to millisecond periods in a past accretion phase by mass and angular momentum transfer from a binary late-type companion (Alpar et al. 1982). Close binary systems with MSPs are a subject of special interest since they are thought to be the missing link between low-mass X-ray binaries (LMXBs) and isolated MSPs. The discovery of the eclipsing binary pulsar system PSR B1957+20 (Fruchter et al. 1988) gave support to this formation scenario.

PSR B1957+20 is in a binary system with a 0.025 $M_\odot$ companion in a 9.16-hr orbital period. It has a spin period of 1.6 ms, the third shortest among all known MSPs. The X-ray emission of PSR B1957+20 is found to be non-thermal dominated and best modeled with a single power-law spectrum, which indicates that the X-rays originate from the shock interaction of the pulsar wind with the wind of the companion star or from the pulsar magnetosphere (Stappers et al. 2003, Huang & Becker 2007). A 4$-\sigma$ detection of X-ray coherent pulsation was reported by Guillemot et al. (2012). In addition, Huang & Becker (2007) found a strong correlation of the pulsar’s X-ray flux with its orbital period. However, due to the short exposure we could not know whether the flux modulation was periodic and given the limited photon statistics it was not possible to investigate any spectral variation as a function of orbit phase or to determine the exact geometry of the peak emission. Repeated coverage of the binary orbit in a longer Chandra observation would provide us a better photon statistic and allow us to determine the emission geometry with higher accuracy.
2. Observation and data analysis

A Chandra observation aimed on PSR B1957+20 was performed on 2008 August 15 (ObsID 9088) with an uninterrupted 169-ks exposure. Data reduction and analysis were processed with Chandra Interactive Analysis Observations (CIAO) version 4.3 software and the Chandra Calibration Database (CALDB) version 4.4.1. The level 1 data with background cleaning were used in our study. Data analysis was restricted to the energy range of 0.3 – 8.0 keV. For the timing and spectral analyses, we extracted the photons from a circular region centered at the radio timing position†, RA(J2000)=19h59m36.77s, Dec=20°48′15.12″, with a radius of 2″.

2.1. Timing Analysis

For the timing analysis, we first extracted the photons from the aforementioned circle and translated the photon arrival times to the solar system barycenter by using the CIAO tool axbary. The JPL DE200 solar system ephemeris was used for the barycentric correction to ensure consistency with the radio ephemeris.

As the Chandra observation covers over five consecutive binary orbits, by plotting a light curve of the X-ray source counts versus the orbital phase we can confirm that the X-ray flux is not steady with time. We also applied a Kolmogorov-Smirnov (KS) test to the unbinned light curve data in order to have a bin-independent statistical evaluation of the X-ray emission variability. In addition, to search for a modulation of the X-ray flux as a function of orbital phase, we selected X-ray data covering 5 complete and consecutive orbits and then used the radio timing ephemeris of PSR B1957+20 from a pulsar catalog provided by Lucas Guillemot‡ to fold a light curve at the orbital period (see Fig 1 left panel). Using a χ²-test, the significance for a flux modulation over the observed orbit was found to be ∼ 99%.

2.2. Spatial Analysis

Fig 1 (right panel) shows the Chandra ACIS-S3 image in the energy band 0.3–8 keV of the field around PSR B1957+20. This image was created by using an adaptive smoothing algorithm with a Gaussian kernel of σ < 3 pixels in order to probe the detailed structure of faint diffuse emission. Both the pulsar and an extended X-ray feature (hereafter the “tail”), protruding from the pulsar position, can be clearly seen in this image. The length of the tail with its orientation to the northeast is about 25 arcsec.

2.3. Spectral Analysis

Assuming that the X-ray emission originates from the intra-binary shock or the pulsar’s magnetosphere (Stappers et al. 2003, Huang & Becker 2007, Guillemot et al. 2012), we expect the radiation to be synchrotron. To test this hypothesis, we fitted the spectrum with an absorbed power-law model (PL). Unexpectedly, a single PL model cannot provide any statistically acceptable description of the observed spectrum. We also tested whether a single blackbody (BB) model, a double PL model, a PL+BB, a MEKAL, a thermal bremsstrahlung (TB), a MEKAL+PL, and a PL+TB model can provide an appropriate modeling of the data. We found those models cannot yield a better or an acceptable description. Therefore, we suspect a dependence of the X-ray spectrum of PSR B1957+20 on its orbital phase due to the variability observed in its X-ray flux level which seems to correlate with its orbital period.

To investigate whether the X-ray spectral behavior of PSR B1957+20 varies across the

† from the ATNF Pulsar Catalogue
orbit, we analysed the X-ray spectra within the orbital phase of $\phi = 0.05 - 0.45$ which covers the eclipsing region and outside the aforementioned region ($\phi = 0.45 - 1.05$) separately. We found that the binary-phase resolved spectral analysis reveals a non-thermal emission nature of the detected X-rays and each of the observed spectra can be well described by a single PL model with different photon indices, which indicates that its spectral behavior is orbital dependent.

We selected a box of $16'' \times 6''$ with an orientation along the proper motion direction as the region of the X-ray tail of PSR B1957+20 and found an absorbed single PL model fits the X-ray spectrum of the tail well, which implies that the X-ray emission originates from the pulsar interaction with the ambient medium. A softening of the spectrum of the X-ray tail as a function of the distance from the pulsar is expected if synchrotron cooling of the particles injected at the termination shock is dominated. For the purpose of investigating the possible spectral variation, we performed a spatially-resolved spectral analysis using two separate extraction regions along the tail. An indication for such a spectral variation was found in this study.

3. Summary and conclusion

We have searched for the orbital modulation of the X-ray emission from PSR B1957+20. Analysing the data with a $\chi^2$-test and a K-S test revealed a marginal intra-orbital flux modulation, which suggests that the non-thermal X-rays from PSR B1957+20 are mostly due to intra-shock emission at the interface between the pulsar wind and the ablated material from the companion star. The pulsar wind electrons and positrons are accelerated and randomized by the shock and emit the X-rays via the synchrotron process.

References

Neutron stars: history of the magnetic field decay

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Abstract.
Using the data of the ATNF pulsar catalog we study the relation connected the real age \( t \) of young neutron stars (NS) and their spin-down age \( \tau \). We suppose that this relation is independent from both initial period of the NS and its initial surface magnetic field, and that the laws of the surface magnetic field decay are similar for all NSs in the Milky Way. We further assume that the birth-rate of pulsars was constant during at least last 200 million years. With these assumptions we were able to restore the history of the magnetic field decay for the galactic NSs. We reconstruct the universal function \( f(t) = B(t)/B_0 \), where \( B_0 \) is the initial magnetic field and \( B(t) \) is the magnetic field of NS at the age \( t \). The function \( f(t) \) can be fitted by a power law with power index \( \alpha = -1.17 \).

Keywords. methods: data analysis, methods: statistical, stars: neutron, magnetic fields, pulsars: general

1. Introduction
Magnetic fields determine observational manifestations of neutron stars. Soon after the discovery of the first radio pulsars, the decay of their magnetic field was supposed by Ostriker & Gunn (1969). Therefore comprehension of magnetic fields behavior aids not only in more accurately finding real pulsar ages, but also helps us understand the physical processes inside isolated neutron stars.

First of all we carefully consider behavior of spin-down age of radio pulsar:

\[
\tau = \frac{P}{\dot{P}}. \tag{1.1}
\]

Here \( P \) is period of pulsar and \( \dot{P} \) is its derivative. It appears that \( \tau \) is highly sensitive to changes in magnetic fields of NS. We find that it is possible to introduce an additional real pulsar age estimation based on the counts of pulsars with fixed spin-down age \( \tau \). If we suppose that the law governing magnetic-field decay is identical for all pulsars, and can be present by the formula \( B(t) = B_0 f(t) \), then it is possible to restore the dimensionless factor \( f(t) \) irrespectively of initial pulsar period distribution and initial distribution of their magnetic fields. This factor can be expressed as

\[
f(t) = \exp \left( \int_0^t \frac{dt'}{2\tau(t')} \right) / \sqrt{\tau(t)} \tag{1.2}
\]

The algorithm and detailed description of our method of restoring the function \( f(t) \) is described in Igoshev (2012). Here we discuss the effects of the observational selection.
2. Selection effects

Results of restoring the function \( f(t) \) by our method might be distorted by the significant observational selection effects. In fact, we observe only a small part of all galactic pulsars. And we can not be sure exactly that this small part correctly reproduces characteristics of the whole galactic ensemble of the NSs. Indeed, selection effects are able to hide some group of pulsars from our attention. In this case the selection effects can change an average and a variance of the parameters of the whole ensemble of the NS distribution.

On the other hand it is difficult to estimate this selection effects theoretically because of our poor understanding of the radiation mechanism for pulsars. Therefore, we will carefully analyze the observational data. We select the isolated radio-pulsars excluding the millisecond pulsars from the ATNF pulsar catalog by (Manchester et al. 2005)†. We divide them into five groups, where the spin-down age \( \tau \) is expressed in years:

- \( \tau \in [700 - 1.2 \cdot 10^5] \)
- \( \tau \in [1.2 \cdot 10^5 - 4.5 \cdot 10^5] \)
- \( \tau \in [4.5 \cdot 10^5 - 9.6 \cdot 10^5] \)
- \( \tau \in [9.6 \cdot 10^5 - 1.6 \cdot 10^6] \)
- \( \tau \in [1.6 \cdot 10^6 - 6 \cdot 10^6] \)

and plot their cumulative distribution over their distance from the Sun in Fig. 1. It is clear that for pulsars of middle ages \( \tau \in [1000, 1.6 \cdot 10^6] \) the radial distributions are similar. The Kolmogorov-Smirnov test confirms, with a probability of more than 99%, that these four samples can be described by a single distribution function. On the other hand the radial distribution of the group of older pulsars with \( \tau \in [4 \cdot 10^6, 6 \cdot 10^6] \) years is different. Therefore, our conclusions below are correct only for pulsars from the four first age intervals.

Let us consider a cylinder in the Galaxy, centered on the Sun, with a radius 10 kpc and with its axis normal to the Galactic plane. Our selection is similar to those by Lyne et al. (1998), but with a larger cylinder radius. As we study the relative quantities, the total number of objects which fall in the cylinder is not important.

We can show that the observational selection which does not conceal pulsars with certain ages is harmless for our analysis. Let us divide our cylinder with 10 kpc radius into two parts: the inner cylinder A with radius 1.5 kpc and remained part B of the large cylinder. The objects in cylinder A are belong to the local pulsar population. Designate the number of pulsars with spin-down ages in the interval \([\tau, \tau + \Delta \tau]\) inside the cylinder A as \( n_\alpha \) and as \( n_\beta \) for those which are in part B of the large cylinder. For second interval of the spin-down ages \([\tau', \tau' + \Delta \tau]\) we designate the corresponding values as \( n_\gamma \) in A and \( n_\delta \). As it known from paper by Lyne et al. (1998) the observational selection effects are weak for object in the cylinder A. Therefore, we can estimate the ratio \( n_\alpha / n_\gamma \) with high level of confidence. As it was discussed above the radial distribution function for pulsars of different spin-down ages are similar. It means that

\[
\frac{n_\beta}{n_\alpha} = \frac{n_\delta}{n_\gamma}
\]  

(2.1)

Gathering the pulsars from parts A and B of the large cylinder together we can write the next relation:

\[
\frac{n_\alpha + n_\beta}{n_\gamma + n_\delta} = \frac{n_\alpha (1 + n_\delta / n_\gamma)}{n_\gamma (1 + n_\delta / n_\gamma)} = \frac{n_\alpha}{n_\gamma}
\]  

(2.2)

We find that the count of pulsars in the large cylinder does not change the result. In the other hand, the larger number of pulsars located in the large cylinder allows us to make more precise conclusions.

† http://www.atnf.csiro.au/research/pulsar/psrcat/
Figure 1. Cumulative distribution of the pulsars over distances from the Sun. The electronic version of article contains color figures. Here red solid line corresponds to ages $\tau \in [700, 1.2 \cdot 10^{5}]$ years, green dashed line — to $\tau \in [1.2 \cdot 10^{5}, 4.5 \cdot 10^{5}]$ years, blue short-dashed line — to $\tau \in [4.5 \cdot 10^{5}, 9.6 \cdot 10^{5}]$ years, violet dotted line — to $\tau \in [9.6 \cdot 10^{5}, 1.6 \cdot 10^{6}]$ years and sky blue dashed and dotted line - to $\tau \in [4 \cdot 10^{6}, 6 \cdot 10^{6}]$ years. Each interval of ages includes about of 100 pulsars.

3. Results

A new statistical method which allows us to restore history of magnetic fields decay for middle age neutron stars was developed by Igoshev (2012). This method was applied to a real sample of radio pulsars from the ATNF catalog. We find that the surface magnetic fields of middle age radio pulsars decay following a modified power law:

$$f(t) = \left( \left( \frac{t}{t_0} \right)^\gamma + c \right)^{-1}$$  \hspace{1cm} (3.1)

with parameters $\gamma = 1.17$, $a = 0.034$, $c = 0.84$ and $t_0 = 10^4$ years. It was found that observational selection is negligible when we take into consideration only part of all galactic volume. This effect is connected with similarity of radial distribution for radio pulsars of different ages in range $[700 - 1.6 \cdot 10^6]$ years.

We also estimate the pulsar birthrate supposing that pulsars with the spin-down age over $4 \cdot 10^4$ years have not experienced significant magnetic-field decay. This produces a birth rate of about 2.9 pulsars per century.

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Population synthesis of young neutron stars
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Abstract. We investigate the fortune of young neutron stars (NS) in the whole volume of the Milky Way with new code for population synthesis. We start our modeling from the birth of massive OB stars and follow their motion in the Galaxy up to the Supernova explosion. Next we integrate the equations of motion of NS in the averaged gravitational potential of the Galaxy. We estimate the mean kick velocities from a comparison the model Z and R-distributions of radio emitting NS with that for galactic NS accordingly ATNF pulsar catalog. We follow the history of the rotational velocity and the surface magnetic field of NS taking into account the significant magnetic field decay during the first million year of a neutron star’s life. The derived value for the mean time of ohmic decay is $2.3 \cdot 10^5$ years. We model the subsample of galactic radio pulsars which can be detected with available radio telescopes, using a radio beaming model with inhomogeneous distribution of the radio emission in the cone. The distributions functions of the pulsar periods $P$, period derivatives $\dot{P}$ and surface magnetic fields $B$ appear to be in a close agreement with those obtained from an ensemble of neutron stars in the ATNF catalogue.

Keywords. methods: data analysis, methods: statistical, stars: neutron, magnetic fields, pulsars: general

1. Introduction
The method of population synthesis allows us to probe both the initial state of the modeled ensemble of NSs and details of its evolution. The assumptions about spatial distribution and kinematic of pulsars ensemble were detailed in Igoshev & Kholtygin (2011). Here the principles of survey modeling are reported. Commonly, the model of pulsars survey is based on the radiometer equation (see below for details). We follow this approach with one exception due to modern observational results. We introduce a pulse-width versus period relation based on the consideration by Maciesiak & Gil (2011).

2. Model of survey
A pulsar is detected if its luminosity exceeds the noise at some confidence level. The limiting flux density $S_{lim}$ is given by the radiometer equation:

$$S_{lim} = \frac{\sigma \beta (T_{sky} + T_{rec})}{G \sqrt{N_p \tau_{obs} \delta \nu}} \sqrt{\frac{W_e}{P - W_e}},$$

(2.1)

where $T_{rec}$ is the receiver temperature on cold sky, $T_{sky}$ is the sky background temperature, $G$ is antenna gain, $N_p$ is the number of polarizations, $\delta \nu$ is the receiver bandwidth, $t_{int}$ is the integration time, $P$ is pulsar period, $W_e$ is the effective pulse width, $\sigma$ is a signal to noise threshold and $\beta$ is a constant accounting for various system losses.

The observed pulsar width can be written as following:

$$W_e = \sqrt{W^2 + \tau_{samp}^2 + \left(\frac{t_{samp} D M}{D M_0}\right)^2 + \tau_{scatt}^2}.$$
Here $W$ is the intrinsic pulse width, $t_{\text{samp}}$ is the sampling interval, and $\tau_{\text{scatt}}$ is the pulse broadening due to interstellar scattering. We suggest to take into account observational properties of the half-power widths of core components verified by Maciesiak & Gil (2011):

$$\omega = \frac{2.45P^{-0.5}}{\sin \alpha}$$

(2.3)

Those authors show that this dependence well describes the ensemble of Galactic NSs. In Eq. (2.3), $\alpha$ is an angle between rotational axis and magnetic dipole. This empirical law was firstly introduced by Rankin (1990) in her work for pulsars with inter-pulse emission. Recently, this relation was tested for majority of normal pulsars by Maciesiak & Gil (2011). Moreover, authors noticed that even in case of conal emission pulse-width statistic are in good agreement with Eq. (2.3).

Therefore, instead of classical value $W = 0.05P$ we apply (2.3):

$$W = \frac{6.81 \cdot 10^{-3}}{\sin \alpha} \sqrt{P}$$

(2.4)

The flat angle distribution of the pulsars emission is modeled in our population synthesis. The relation (2.4) naturally explains dispersion of values which is modeled as Gaussian distribution in Lorimer et al. 2006. For the value of $DM_0$ we use its standard definition:

$$DM_0 = \frac{N_{\text{ch}}t_{\text{samp}}\nu^3}{8299\delta\nu_{\text{ch}}}$$

(2.5)

In this expression $\nu$ is the observational frequency and $\delta\nu_{\text{ch}}$ is the receiver bandwidth.

**Figure 1.** Cumulative distribution of the luminosity function $L$ for pulsars. Solid (red) line shows the distribution for Faucher-Giguere & Kaspi (2006) model, dashed (green) line corresponds to our model with suggested by Maciasiek & Gil (2011) pulse-width relation and dotted (blue) line to the sample of isolated radio pulsars from ATNF catalog (Manchester et al. 2005).
We find the relation for $\tau_{\text{scatt}}$ suggested in Lorimer et al. 2006 does not well fit the observational distribution of radio pulsars by their radio luminosities, while the formula suggested by Cordes & Lazio (2002):

$$\tau_{\text{scatt}} = 1.10SM_{\nu}^{6/5}\nu^{-22/5}D,$$

(2.6)
gives a reliable result. Here $SM_{\nu}$ is the scattering measure from the model of electron density in our galaxy NE2001, and $D$ is the distance to the radio pulsar.

To test our model of the population synthesis we calculate the distribution of the radio luminosity $L = SD^2$ for our model ensemble of pulsars. Here $S$ is the pulsar’s radio flux in $\text{Yu}$ at 1400 GHz. The obtained distribution is plotted in Figure 1. A comparison of our data with obtained for population synthesis model by Faucher-Giguere & Kaspi (2006) and for real pulsar ensemble from the ATNF catalog (Manchester et al. 2005) leads us to conclude that our approach produces good agreement with the real luminosity distribution.

3. Conclusions

We show that the Maciesiak & Gil (2011) relation for the intrinsic pulsar width $W$ lets us model the Parkes and Swinburne multibeam surveys with our population synthesis code. We also conclude that the classical model of luminosity by Faucher-Giguere & Kaspi (2006) should be multiplied by factor of eight in order to obtain the correct share of the brightest pulsars in the whole pulsar ensemble.

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Testing the relationship between nulling, drifting and mode-changing

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Abstract. Recent observations, suggesting that subpulse drifting, pulse nulling and profile mode-changes are related phenomena, are reviewed and it is argued that these are associated with global changes in the magnetosphere. Long simultaneous multi-frequency observations are useful to test this premise as is illustrated by the preliminary results from a recent study of PSR B0031−07, B0809+74 and B2319+60. Such observations for a larger sample of pulsars will be useful to constrain recent models, invoking global changes in the pulsar magnetosphere, proposed to explain observations demonstrating association of spin-down changes with profile mode-changes.

Keywords. radiation mechanisms: general, pulsars: general, pulsars: B0031−07, pulsars: B0809+74, pulsars: B2319+60

1. Introduction

A rich diversity is seen in the radio emission in the individual pulses from pulsars. Apart from pulse-to-pulse intensity variations, many pulsars show changes in pulse phase, pulse shapes, pulse widths, number of components in a pulse (subpulses), separation between components and the ratio of intensity in components. In some pulsars, these variations are correlated across several successive individual pulses. Such correlated behaviour is broadly classified in three phenomena. A systematic advancement of subpulse phases with progressively increasing pulse number is called subpulse drifting. PSRs B0809+74 and B0031−07 are two pulsars, which show prominent subpulse drifting, and with different drift modes in the latter pulsar (Lyne & Ashworth 1983; Vivekanand & Joshi 1997). About 100 pulsars, such as B0031−07 and B2319+16, show abrupt cessation of emission for several periods, called pulse nulling (Wright & Fowler 1981; Vivekanand & Joshi 1997). The average profiles of some pulsars, such as B0329+54, switch between two or more stable forms and this is called profile mode-changes (Lyne 1971). While subpulse drifting is believed to be associated with spark discharges in pulsar polar gaps (Ruderman & Sutherland 1975), the mechanism for pulse nulling and mode-changes are not well understood. Although it has been suggested that nulls and profile mode-changes may be geometric in origin, relationship between these phenomena with subpulse drifting, particularly over a wide range of frequencies, in recent studies suggest a more dynamic origin. This aspect is discussed in this paper.

2. Relationship between subpulse drifting, nulling and mode-changes

A change in drift rate during the null and a correlation between the subpulse phase before and after the null was reported in PSR B0809+74 by Lyne and Ashworth (1983). A similar correlation for short nulls (duration 1 to 4 pulses) is seen in PSR B0031−07 (Joshi and Vivekanand 2000). It has not been possible to conduct such studies on other
Vivekanand & Joshi (1997) claimed that the average pulse profiles for PSR B0031−07, formed with pulses corresponding to different drift rates, differ significantly from each other. Although this conclusion was based on single polarisation data from Ooty Radio Telescope, both profile mode-changes and sub-pulse drift are observed as a systematic correlation across a number of pulses and it is plausible that these two are related to each other. A pulse null can also be considered an extreme form of profile mode-change (Wang et al. 2007).

As changes in subpulse drift are believed to be related to magnetospheric changes, relationship of profile mode-changes and nulls with subpulse drift implies that all the three phenomena are results of global magnetospheric changes and are expected to be correlated across a wide range of frequencies. This can be tested by long simultaneous multi-frequency observations of pulsars, exhibiting such phenomena.

3. Simultaneous multi-frequency observations of nulling-drifting pulsars

A handful of pulsars show all the three phenomena. The most prominent and relatively strong pulsars of these are PSR B0809+74, B0031−07, B2319+60 and B2111+46. A study of these pulsars (Gajjar et al. in preparation; Joshi et al. in preparation) is currently in progress and implies such a correlation across a wide range of frequencies.

Figure 1 shows the subpulse drift and average profiles for PSR B0031−07 at 325, 610 and 1480 MHz for the dominant different drift modes A and B of this pulsar (with drift rates -4.05 and -7.78 ms/period at 325 MHz respectively). The drift rates estimated for individual drift bands in PSR B0031−07 for 325, 610 and 1480 MHz are correlated at a high significance across the frequencies (Joshi et al., in preparation). Moreover, the drift rate of the subpulse change at the same time across the frequencies studied.

The bottom panels of Figure 1 show that the profiles, obtained after averaging all periods belonging to a given drift mode, are different for the two modes. The most striking difference between the average profiles for Mode A and B is seen at 610 MHz (middle two plots). While the peak of Mode A profile is at the leading edge, Mode B profile exhibits a peak at the trailing edge. The averaged pulse for the drift mode A arrives earlier than that for mode B at all three frequencies confirming the results of Vivekanand & Joshi (1997). Similar behaviour was seen for PSR B2319+60.

Figure 2 shows the on-pulse intensity as a function of pulse number for PSRs B0031−07 and B2319+60 respectively. The abrupt drop in the intensity, visible in these plots,
Figure 2. Intensity in the on-pulse window for PSR B0031-07 and B2319+60 for pulses observed simultaneously at 325, 610, 1460 and 4850 MHz.

indicates the nulls, which also appear to be correlated across the frequencies. A more detailed analysis of these data indicates a high degree of correlation between nulling fraction (NF) and null and burst length histograms from 325 MHz to 4.8 GHz (Gajjar et al. in preparation).

4. Discussions

Simultaneous multi-frequency study of a small sample of pulsars, which show pulse nulling, subpulse drifting and profile mode changes, suggests that these phenomena are broadband and related to each other. This correlation is consistent with the recent detailed studies of single pulse emission from other pulsars such as B1822-09, B0943+10 (See van Leeuwen et al., this volume). If such a relationship does indeed exist for all the pulsars, then the changes in spin-down rate associated with extended off and on-emission duration of intermittent pulsars such as PSR B1931+24 (Kramer et al. 2006) and with the profile mode-changes reported by Lyne et al. (2010) link the three phenomena to changes in particle outflow density in the pulsar wind. While it is not clear what causes these changes, models invoking global changes in pulsar magnetosphere have recently been proposed (Timokhin 2010). Thus, it appears that subpulse drifting, nulling and profile mode-changes are all manifestations of global changes in magnetosphere. Future long simultaneous observations of these phenomena at widely separated frequencies will be very useful for constraining such models.

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Distribution of ionized gas density measured by differential VLBI Observations of pulsars

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Abstract. Differential VLBI observations of pulsars in our Galaxy can derive trigonometric parallax of them. Distance to pulsars derived by the parallax are very important to estimate some mean density of ionized gas between pulsars and the earth using rotation measures of them. Some preliminary results of distribution of the ionized gas density in our galaxy by using previous VLBI results are shown. Possibility of VLBI observations of pulsars using VERA and the other VLBI antennas will be described.
Gamma-ray emission from pulsar binaries

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Abstract. Pulsar winds, containing charged particles, waves and a net (phase-averaged) magnetic field, are thought to fuel the high-energy emission from several gamma-ray binaries. They terminate where the ram pressure matches that of the surroundings - which, in binaries, is provided by the wind of the companion. Before termination, pulsed emission can be produced by inverse Compton scattering of photons from the companion by particles in the waves. After termination, both the bulk kinetic energy of the particles and the Poynting flux in the waves are dissipated into an energetic particle population embedded in the surviving phase-averaged magnetic field. Pulsed emission is no longer possible, but a substantial flux of unpulsed high-energy photons can be produced. I will present results showing that the physical conditions at the termination shock can be divided into two regimes: a high density one, where current sheets in the wind are first compressed by an MHD shock and subsequently dissipate by reconnection, and a low density one, where the wind can first convert into an electromagnetic wave in the shock precursor, which then damps and merges into the wind nebula. The shocks surrounding isolated pulsars fall into the low-density category, but those around pulsars in binary systems, may transit from one regime to the other according to binary phase. The implications of the shock-structure dichotomy for these objects will be discussed.
TeV cosmic-ray electrons from millisecond pulsars

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Abstract. Recent $\gamma$-ray observations by the Fermi Gamma-Ray Space Telescope suggest that the $\gamma$-ray millisecond pulsar (MSP) population is separated into two subclasses with respect to pair multiplicity. Here, we calculate the cosmic-ray electron/positron spectra from MSPs. Based on the assumption of equipartition in the pulsar-wind region, the typical energy of electrons/positrons ejected by an MSP with pair multiplicity of the order of unity is $\sim 50$ TeV. In this case, we find that a large peak in the 10-50 TeV energy range would be observed in the cosmic-ray electron/positron spectrum. Even if the fraction of pair-starved MSPs is 10\%, a large peak would be detectable with future missions such as CALET and CTA.

Keywords. stars: neutron, cosmic rays

1. Introduction

The Fermi Gamma-Ray Space Telescope has detected $\gamma$-ray pulsed emission from more than twenty millisecond pulsars (MSPs; Nolan et al. 2012), which have a rotation angular frequency $\Omega \sim 10^3$ s$^{-1}$ and a stellar surface magnetic field $B_s \sim 10^{8.5}$ G. The detection of GeV emission from a pulsar magnetosphere means that electrons and positrons are accelerated to more than $\sim$50 TeV by the electric field parallel to the magnetic field, which arises in a depleted region of the Goldreich-Julian (GJ) charge density (Goldreich & Julian 1969).

Venter et al. (2009) fitted the pulse profiles of Fermi-detected MSPs with the geometries of the $\gamma$-ray emission regions predicted by different theoretical models. They found that the pulse profiles of the two MSPs show unusual behavior in the $\gamma$-ray light curves and could not be fitted by the geometry of either the outer-gap or slot-gap models. They proposed that these unusual light curves could be fitted by the pair-starved polar-cap model (Muslimov & Harding 2004).

The high-energy electron/positron spectrum ejected from MSPs would be a useful probe for the existence of pair-starved MSPs. Since the lifetimes of MSPs are much longer than those of canonical pulsars (> 10$^{10}$ yr), there should be many more nearby active MSPs. Therefore MSPs could potentially contribute to the observed high-energy cosmic-ray electrons/positrons and will be detectable by next-generation experiments such as the Calorimetric Electron Telescope (CALET; Torii et al. 2008a) and Cherenkov Telescope Array (CTA; CTA Consortium 2010).

In this paper, we investigate the contribution of electrons/positrons ejected from MSPs to the observed cosmic-ray spectrum and show the possibility that the electrons/positrons from these MSPs will be detectable in future observations.
2. The Model

In order to estimate the energy of electrons/positrons available in the wind region and their adiabatic and radiative cooling in the shocked region, we adopt the model of Kashiyama, Ioka & Kawanaka (2011; hereafter KIK11). Although KIK11 considered the case of white dwarf pulsars, the situation is similar to the case of MSPs because they have a long lifetime and the supernova shock front has already decayed. From now on we set fiducial parameters of the MSP’s surface magnetic field strength, angular frequency and radius as $B_0 = 10^{8.5} \text{G}$, $\Omega = 10^{3} \text{s}^{-1}$ and $R = 10^{6} \text{cm}$, respectively.

We assume energy equipartition between the particles and the magnetic field, $\epsilon_e N = B^2/8\pi$, and the conservation of the particle number flux, $4\pi r^2 c N \sim \text{constant}$, in the MSP wind region. Here, $N$ is the number density of electrons/positrons and $c$ is the speed of light. Using these assumptions, the typical energy of electrons/positrons $\epsilon_e$ can be described as

$$\epsilon_e \sim 50\kappa^{-1} \left( \frac{B_0}{10^{8.5} \text{G}} \right) \left( \frac{\Omega}{10^{3} \text{s}^{-1}} \right)^2 \left( \frac{R}{10^6 \text{cm}} \right)^3 \text{TeV},$$

(2.1)

where $\kappa$ is the multiplicity of electrons/positrons. Note that the typical energy depends on the pair multiplicity. We estimate the adiabatic and radiative cooling of electrons/positrons in the shocked region and can conclude that the energy loss of electrons/positrons in a pulsar-wind nebula is not very large (Kisaka & Kawanaka 2012).

The observed electron/positron spectrum after propagation in the ISM is obtained by solving the diffusion equation

$$\frac{\partial}{\partial t} f(t, r, \epsilon_e) = D(\epsilon_e) \nabla^2 f + \frac{\partial}{\partial \epsilon_e} (P(\epsilon_e) f) + Q(t, r, \epsilon_e),$$

(2.2)

where $f(t, r, \epsilon_e)$ is the energy distribution function of electrons/positrons, $D(\epsilon_e) = D_0 (1 + \epsilon_e/3\text{GeV})^{\delta}$ is the diffusion coefficient, $P(\epsilon_e)$ is the cooling function of the electrons/positrons, which takes into account synchrotron emission and inverse Compton scattering during the propagation, and $Q(t, \epsilon_e, r)$ is the injection term. Here we adopt $D_0 = 5.8 \times 10^{26} \text{cm}^2\text{s}^{-1}$, $\delta = 1/3$.

3. Result and Discussion

We calculate the cosmic-ray electron/positron spectra from pair-starved MSPs. We set the pair multiplicity $\kappa = 1$, lifetime $\tau = 5 \times 10^{10} \text{yr}$, total energy $E_{\text{rot}} = 10^{52} \text{erg}$, local birth rate $R = 3 \times 10^{-9} \text{yr}^{-1} \text{kpc}^{-2}$ and the fraction of energy lost due to synchrotron emission as 30 per cent for each MSP. We assume that each MSP has the same parameter values ($B_0 = 10^{8.5} \text{G}$, $\Omega = 10^{3} \text{s}^{-1}$, $R = 10^{6} \text{cm}$), because most MSPs have almost the same spin-down luminosity. For the injection distribution function, we assume a mono-energetic distribution equation with energy $\epsilon_e = 50 \text{ TeV}$.

In Fig. 1, the electron/positron flux from multiple pair-starved MSPs is shown. It is very interesting that there is a large peak at 10-50 TeV energy range. We should detect the electron/positron flux with near-future missions such as CALET and CTA.

It was considered that the number of astrophysical sources contributing to the energy range above several TeV is quite small, according to the birth rate of supernovae and canonical pulsars in the vicinity of Earth (Kobayashi et al. 2004; Kawanaka, Ioka & Nojiri 2010; Kawanaka et al. 2011). However, we find that it is possible for multiple pair-starved MSPs to contribute to the 10-TeV energy range in the electron/positron spectrum. Therefore, if the anisotropy of observed electrons/positrons is weak in that range, we suggest that pair-starved MSPs may contribute to the spectrum significantly.
Figure 1. Electron/positron spectrum predicted from MSPs with a fraction of pair-starved MSPs of 100% (thin solid line) and its sum (thick solid line) together with the background (thin-dashed line). The injection distribution function is a mono-energetic distribution with energy $\varepsilon_e = 50$ TeV and multiplicity $\kappa = 1$. Data points correspond to measurements of ATIC (boxes, purple; Chang et al. 2008), HESS (asterisks, light green and black; Aharonian et al. 2008, 2009), PPB-BETS (triangles, yellow; Torii et al. 2008b), Fermi (shaded circles, blue; Ackermann et al. 2010) and GRAPES (black empty circles: Kistler & Yüksel 2009). We also show the total spectra from pair-starved MSPs with different fractions: 25% (thick-dashed line) and 10% (dot-dashed line). We assume that the lifetime $\tau = 5 \times 10^{10}$ yr, total energy $E_{\text{rot}} = 10^{52}$ erg, local birth rate $R = 3 \times 10^{-9}$ yr$^{-1}$ kpc$^{-2}$ and the fraction of energy loss is 30% (Kisaka & Kawanaka 2012)

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Infrared AKARI observations of magnetars 4U 0142+61 and 1E 2259+586

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Abstract. We observed two magnetars, 4U 0142+61 and 1E 2259+586, with the Japanese infrared satellite AKARI to search for the time variability at wavelengths between 2-4 µm. We significantly detected 4U0142+61 in the 4µm band, and determined flux upper limits in the other two bands. We did not detect 1E 2259+586 in any of the bands, and determined upper limits. Comparing the detection of 4U 0142+61 in the 4µm band with the Spitzer observation from 2005, we found the flux was reduced to be 64%. We interpret this time variability in the infrared band as an increase of the inner radius of the dust disk around the neutron star, where the increase is due to the sublimation of the dust by the large flare of neutron star itself.

Keywords. stars: neutron – infrared: stars – X-rays: individual (4U 0142+61, 1E 2259+586)

1. Introduction

Magnetars are neutron stars with ultra-strong magnetic fields (10¹⁴–10¹⁵ G). They emit X-ray and gamma-ray photons by releasing magnetic energy; however their exact emission mechanism is still an open question. Therefore these sources have been intensively observed, at multiple wavelengths from radio to gamma-rays, to reveal that emission mechanism.

Some magnetars have optical and infrared (IR) counterparts. The most luminous magnetar, 4U 0142+61, is a 8.7 s pulsar and its IR-optical counterpart has been most intensively observed. In the Spitzer observation, a mid-IR hump was discovered in the spectral energy density. While the optical component is demonstrably of magnetospheric origin, the mid-IR component may arise from a dust disk around the magnetar (Wang et al. 2006). So far no time variability was reported for the dust disk component. The 7 s pulsar 1E 2259+586, has been also detected in the mid-IR band, but there was no mid-IR hump (Kaplan et al. 2009).

Here, we report on our IR observations of 4U 0142+61 and 1E 2259+586 with the Japanese infrared satellite AKARI. The bands AKARI observed, 2–4µm, are thought to be dominated by the dust disk. The main purpose of our study is to search the time variability of this min-IR component.

We will present the details of our results in this paper.
2. Observational results of 4U 0142+61 and 1E2259+586 with AKARI/IRC

We carried out imaging observations of 4U 0142+61 and 1E 2259+586 with AKARI/IRC in 2009 and 2010. The 2\(\mu\)m and 4\(\mu\)m bands have been observed with terrestrial telescopes and Spitzer, but only AKARI/IRC can observe the 3\(\mu\)m band, which is dominated by the dust disk component. Therefore, this 3\(\mu\)m observation is important to test the dust disk model.

We performed PSF photometry for the position of 4U 0142+61 and 1E 2259+586. Figure 1 shows the 2-4\(\mu\)m images of 4U 0142+61. We could significantly detect 4U 0142+61 at the pulsar position in 4\(\mu\)m image. But, unfortunately, there was no significant detection of 4U 0142+61 in either the 2\(\mu\)m or 3\(\mu\)m band. Therefore we determined the upper limit of the infrared flux of these bands. Magnetar 1E 2259+586 could also not be detected in two bands, 2\(\mu\)m and 3\(\mu\)m, and there too we determined the upper limit of the flux. Figure 2 shows the spectral energy distribution of these two magnetars. The left and the right panel show the results of 4U 0142+61 and 1E 2259+586, respectively.

We discovered the flux of 4U 0142+61 in the 4\(\mu\)m band decreased to 64% of the previous flux obtained by Spitzer observation in 2005 (6.4 \(\sigma\)). Our result suggests that the MIR emission from 4U 0142+61 is variable.

Figure 1. Infrared images of 4U 0142+61. These images were taken with AKARI/IRC in 2009. Left, middle, and right pannel shows 2\(\mu\)m, 3\(\mu\)m, and 4\(\mu\)m bands images respectively. The blue circle in all images (upper right of all images) shows the position of 4U 0142+61.
3. Discussion

In this discussion, we concentrate on the result on 4U 0142+61.

Before our two AKARI observations in 2009 and 2010, we found a large flare from 4U 0142+61 in the RXTE ASM light curve (Kohmura et al. 2012). Assuming the "dust disk model" as the infrared emission mechanism, that dust disk was expected to be heated and sublimated by this large flare.

If the X-rays produced by the large flare of the central X-ray pulsar have energies large enough to sublimate the disk, the inner part of disk will vanish and then inner radius increased. As a result, the size of dust disk decrease, and the infrared flux must decrease too.

To check this scenario, we applied an X-ray heated disk model (Vertilek et al. 1990) as the dust disk around magnetar and calculated the energy spectra by changing the inner disk radius as shown in Fig 2. In the X-ray heated disk mode, the temperature of the disk is a function of radius from the central neutron star. For the temperature distribution in our calculation, we follow the model shown in Wang et al. (2006). This model has five parameters, the value of inclination angle \( i \), distance to the source \( d \), albedo of the disk \( \eta \), outer radius of disk \( r_{\text{out}} \), and inner radius of disk, \( r_{\text{in}} \).

In our calculation, we fixed four parameters without \( r_{\text{in}} \) and changed inner radius of disk. As a result, we succeeded in describing the infrared flux variability by only changing the inner radius of the dust disk.

References

Magnetic field evolution in magnetars

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Abstract. Dynamics of magnetic field decay is numerically studied. For neutron stars with strong magnetic fields, the Hall drift timescale in their crust is very short, and therefore the evolution is significantly affected. The nonlinear coupling between poloidal and toroidal components of the magnetic field is studied. It is also found that the polar field at the surface is highly distorted during the Hall drift timescale. For example, polar dipole field-strength temporarily decreases not by dissipation but by advection. This fact suggests that the dipole field-strength is not sufficient to determine the border between pulsars and magnetars.

Keywords. magnetic fields, stars: neutron, pulsars

1. Introduction

The recent discovery of magnetars with weak fields (SGR0418+5729; Rea et al. 2010), Swift J1822.3-1606 (SGR1822-1606; Rea et al. 2012) and hopefully their similar objects in the future observation may be crucial to understand the magnetic field and its evolution in an isolated neutron star. Their dipole field-strengths inferred from the spin and its time-derivative are \( B \approx 7.5 \times 10^{12} \) G for SGR0418+5729 and \( B \approx 2.7 \times 10^{13} \) G for Swift J1822.3-1606. Thus, there is no clear boundary between magnetars and radio pulsars with respect to the dipole field strength. Their activity may be explained by hidden magnetic fields such as poloidal components with higher-order multipoles or internal toroidal components. In either case, the field strength should be greater than \( B = 10^{14} \)-\( 10^{15} \) G, since other energy sources are insufficient for the activity.

The Hall drift is very important for the magnetic field evolution with \( B > 10^{14} \) G in a neutron star crust. The equation becomes non-linear for the field strength, and the dynamics should inevitably be complicated. Several numerical simulations have been performed so far (Naïto & Kojima (1994), Shalybkov & Urpin (1997), Hollerbach & Rüdiger (2002), Hollerbach & Rüdiger (2004), Pons & Geppert (2007)). The results may depend on the initial condition, conductivity and the crust thickness, and are not easy to be understood due to the non-linearity. For our better understanding, we here provide some numerical results even in a simple model (Kojima & Kisaka 2012).

2. Nonlinear system of poloidal and toroidal fields

The magnetic field decay is governed by a diffusion equation. In the presence of the Hall drift, which is important for stronger field strength, the equation becomes nonlinear. The induction equation of the axially symmetric magnetic field is given by

\[
\frac{\partial G}{\partial t} = D(G) + \frac{R_m}{R} (\nabla \times \nabla S) \cdot \hat{\phi},
\]

\[
\frac{\partial S}{\partial t} = D(S) + R_m R \left[ \nabla \times \left( \frac{1}{R^2} (D(G) \nabla G + S \nabla S) \right) \right] \cdot \hat{\phi}.
\]
where $\mathcal{D}$ is given in cylindrical coordinates $(R, \phi, Z)$ by

$$
\mathcal{D}(G) = \left( R \frac{\partial}{\partial R} \frac{1}{R} \frac{\partial}{\partial R} + \frac{\partial^2}{\partial Z^2} \right) G. \quad (2.3)
$$

The functions $G$ and $S$ describe poloidal and toroidal fields of magnetic fields $\vec{B}$:

$$
\vec{B} = \frac{1}{R} (\vec{\nabla} G \times \vec{e}_\phi) + \frac{S}{R} \vec{e}_\phi, \quad (2.4)
$$

The second terms in eqs. (2.1) and (2.2) come from the Hall drift, and they are complicated non-linear coupling. The magnetized parameter $R_m$, which is a ratio of the Ohmic decay timescale $\tau_d$ to Hall drift timescale $\tau_H$, acts as effective coupling constant.

3. Distortion of dipole field

Numerical results are given in Figure 1 of the evolution for a mixed magnetic configuration consisting of poloidal and toroidal fields. The initial configuration is given solely by the $l = 1$ component for both fields. The maximum of each field is chosen as the same amplitude, and the magnetized parameter is $R_m = 10^2$.

Oscillatory behavior is clearly evident in the magnetic flux function $G$. Initially, the function decreases with the increase in cylindrical distance, and the maximum is located on the equator $\theta = \pi/2$. The maximum moves ‘upward’ in the meridian plane, toward $\theta < \pi/2$, until $t/\tau_d \approx 1.4 \times 10^{-3}$ (second panel). It then changes direction and goes ‘downward,’ passing through the equator at $t/\tau_d \approx 3.2 \times 10^{-3}$ (third panel) and reaching a minimum at $t/\tau_d \approx 5.2 \times 10^{-3}$ (fourth panel), before returning to the initial position at $t/\tau_d \approx 7.8 \times 10^{-3}$ (fifth panel). During this cycle, the field strength decreases.

![Figure 1](image-url)  

**Figure 1.** Snapshots of the evolving fields, $G$ and $S$ at representative times. The gray-scale contour represents the function $S$ of the toroidal field, and lines denote the contour of the magnetic flux function $G$ of the poloidal field. Contour lines outwardly represent the level of $G$ for $0.02 \times n \times (B_0 r_s)$, $n = 1, 2, \cdots$. Gray-scale contour represents $S$ normalized by $B_0 r_s$. Note that different scales are used, since $S$ becomes very small at the bounces in the second and fourth panels. Those panels use the gray scale on the left; the others, the scale on the right. Color scale version is available in Kojima & Kisaka (2012).
The function $S$ is also oscillatory. The initial configuration contains only the $l = 1$ component in the angular part ($S \propto \sin^2 \theta$), which is symmetric with respect to $\theta = \pi/2$. The state at $t/\tau_d \approx 1.4 \times 10^{-3}$ (second panel) markedly differs from the initial state. The configuration is no longer symmetric, and higher multipoles can be seen. The field strength itself is weak around this time. At $t/\tau_d \approx 3.2 \times 10^{-3}$ (third panel), the configuration again becomes symmetric like the initial state, but the sign of $S$ is reversed. The $l = 1$ component is dominated there. After the direction of $B_\phi(= S/(r \sin \theta))$ again changes, the configuration returns to the initial one at $t/\tau_d \approx 7.8 \times 10^{-3}$ (fifth panel). The directional change occurs around $t/\tau_d \approx 1.4 \times 10^{-3}$ (second panel) and $5.2 \times 10^{-3}$ (fourth panel), which correspond to a local minimum of toroidal field strength. The overall toroidal field strength also decreases during this cycle.

This kind of oscillatory behavior is evident only when the toroidal field dominates. Typical timescale of the variation is the Hall drift one $\sim 10^5 - 10^6$ ($B_0/10^{13}\text{G}$)$^{-1}$ years, which is much smaller than that of Ohmic decay $\sim 10^8 - 10^9$ years. Contrarily, if the dipole dominates initially, the configuration is stable until its decay on a timescale $\sim 10^8 - 10^9$ years. There is a great ambiguity in the field-strength and configuration of the initial magnetic fields, so that the theoretical model at present can not predict unique evolutionary track, but gives a hint to the observation.

4. Implication

The magnetars are thought to be young $< 10^5$ years, so that it is rather difficult for the dipole field to decay within this timescale. Instead, the surface magnetic field is highly distorted from the pure dipole due to strong internal toroidal field, as demonstrated in the magnetic evolution. The dipole field is no longer constant. The characteristic age of the magnetars may be inaccurate, since it is derived by a constant dipole field. The age of SGR0418+5729 is $2.4 \times 10^7$ years (Rea et al. 2010), but may not represent the ‘true’ age. Rather, the low-field magnetars, SGR0418+5729 and Swift J1822.3-1606 may correspond to a temporary young phase of oscillatory evolution in which the surface dipole component is not so large, but there is a strong internal toroidal component.

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Recoil velocity of pulsar/magnetar induced by magnetic dipole and quadrupole radiation

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Abstract. Recoil velocity is examined as a back reaction to the magnetic dipole and quadrupole radiations from a pulsar/magnetar born with rapid rotation. The model is extended from notable Harrison-Tademaru one by including arbitrary field-strength of the magnetic quadrupole moment. The process is slow one operating on a spindown timescale. Resultant velocity depends on not the magnitude, but rather the ratio of the two moments and their geometrical configuration. The model does not necessarily lead to high spatial velocity for a magnetar with a strong magnetic field. This fact is consistent with the recent observational upper bound. The maximum velocity predicted with this model is slightly smaller than that of observed fast-moving pulsars.

Keywords. magnetic fields, stars: neutron, pulsars

1. Introduction

Formation of black holes and neutron stars is one of violent energetic events in astronomy. Proper motion of the compact stars may be a relic of the dramatic events at birth. This kind of idea has been discussed since the beginning of relativistic astrophysics in the 1970s. Manchester, Taylor & Van (1974) for the first time determined the proper motion of PSR 1133+16, using timing observation over a four-year period. Since then, the observational progress is remarkable. The statistical property becomes better by increasing the sources (e.g., Hobbs et al. 2005). Observation of magnetars may become a key. They have much strong magnetic field strength $B_s \sim 10^{14-15}$G, so that some of them might have larger velocity, if the kick is caused by some magnetic effects. At moment, the upper limit of the transverse velocity $v_\perp$ has been reported, although there is uncertainty in the value. For example, $v_\perp \sim 210$ km s$^{-1}$ for AXP XTEJ1810-197 (Helfand et al. 2007), $v_\perp < 1300$ km s$^{-1}$ for SGR 1900+14 (Kaplan et al. 2009; De Luca et al. 2009) and $v_\perp < 930$ km s$^{-1}$ for AXP 1E2259+586 (Kaplan et al. 2009). On the other hand, the magnetic fields of the fast moving pulsars are quite ordinary, $B_s \sim 2-3 \times 10^{12}$G. Thus, there is no clear correlation between the field strength and the velocity in the present sample.

Theoretically, a number of the pulsar kick mechanisms have been proposed; see e.g., Lai, Chernoff & Cordes (2001) for a review. Among several kick mechanisms operative at the supernova explosion, a strong magnetic field ($> 10^{15-16}$G) is assumed to produce one preferable direction. The origin of the strong fields is also a problem, fossil or dynamo action. Kick mechanisms at birth end on a dynamical timescale of the order of milliseconds or the cooling timescale of $\sim 10$ s. If the strong magnetic fields are generated on a longer timescale, some natal kick mechanisms involved the magnetic-field-driven anisotropy do not work effectively.

Recoil driven by electromagnetic radiation, which is operative on a longer spindown timescale of $\sim 10^2 (B/10^{13}G)^{-2} (P_i/1\text{ms})^2$ s, has been proposed as a post-natal kick mechanism (Harrison & Tademaru 1975; and Lai, Chernoff & Cordes 2001 for the corrected...
2. Radiation of energy and linear momentum

We consider a rotating object with angular frequency $\Omega$; the object has a magnetic dipole moment $\mu$ and quadrupole moment $Q$. Each direction of the moment is inclined from the spin axis by $\chi_i (i = 1, 2)$. The energy $L$ and linear momentum $F$ radiated per unit time are calculated as

$$L = \frac{2\mu^2 \Omega^4}{3c^3} \sin^2 \chi_1 + \frac{Q^2 \Omega^6}{160c^3} \sin^2 2\chi_2 + \frac{2Q^2 \Omega^6}{5c^5} \sin^4 \chi_2, \quad (2.1)$$

$$F = \frac{\mu Q \Omega^5}{20c^5} \sin \chi_1 \sin 2\chi_2 \sin \delta. \quad (2.2)$$

Three terms in eq.(2.1) are the magnetic dipole radiation $M_{1,1}$, quadrupole radiation $M_{2,1}$ and $M_{2,2}$ respectively. The linear momentum flux arises from the interference between $M_{1,1}$ and $M_{2,2}$. The angle $\delta$ in eq.(2.2) is an azimuthal angle between the dipole and quadrupole directions.

These expressions are compared with those in the off-center dipole model. They are written in term of the magnetic dipole moment $(\mu_R, \mu_\phi, \mu_z)$ in cylindrical coordinate and distance $s$ from the spin axis as follows:

$$L = \frac{2\Omega^4}{3c^3} (\mu_R^2 + \mu_\phi^2) + \frac{4\Omega^6}{15c^5} s^2 \mu_z^2, \quad (2.3)$$

$$F = \frac{8\Omega^5 s \mu_\phi \mu_z}{15c^5}, \quad (2.4)$$

The first term in eq.(2.3) is the magnetic dipole radiation $M_{1,1}$. Corresponce to our expression (2.1) is clear by replacing $\mu_R^2 + \mu_\phi^2 = \mu^2 \sin^2 \chi_1$. The second term in eq.(2.3) is a sum of $\Omega^6 s^2 \mu_z^2/(6c^5)$ by electric dipole radiation $E_{1,1}$, and $\Omega^6 s^2 \mu_z^2/(10c^5)$ by magnetic quadrupole radiation $M_{2,1}$. The parameter in the off-center dipole model corresponds to $Q \sin 2\chi_2 = 4s\mu_z$ except for a complex phase factor. There is a constraint on the quadrupole moment $Q$ as $Q \sin 2\chi_2 \leq 4\mu R_s \cos \chi_1$, since $s \leq R_s$. In the dipole-quadrupole model, it is possible to consider the case of $Q \gg \mu R_s$ in magnitude. Net linear momentum flux (2.4) arises from two types of interference: $\Omega^5 s \mu_\phi \mu_z/(3c^5)$ between $M_{1,1}$ and $E_{1,1}$, and $\Omega^5 s \mu_\phi \mu_z/(5c^5)$ between $M_{1,1}$ and $M_{2,1}$. The latter reduces to eq.(2.2) if $s \mu_z = Q \sin 2\chi_2/4$ and $\mu_\phi = \mu \sin \chi_1 \sin \delta$.

Although there is a slight difference in the radiative components between the off-center dipole and dipole-quadrupole models, both formulae for eqs. (2.1),(2.2) and eqs. (2.3),(2.4) are parameterized as

$$L = \alpha \frac{\mu^2 \Omega^4}{c^3} + \beta \frac{Q^2 \Omega^6}{c^5}, \quad F = \frac{\gamma \mu Q \Omega^5}{10c^5}, \quad (2.5)$$

where $\alpha$, $\beta$ and $\gamma$ are dimensionless numbers that depend on only the geometrical configuration. The typical values are listed in Table, assuming that $\sin \chi_1, \sin \delta \rightarrow 1/\sqrt{2}$, that is, the directional average of $\langle \sin^2 \chi_1 \rangle = \langle \sin^2 \delta \rangle = 1/2$. It is clear that the coefficient $\beta$ in off-center dipole is considerably smaller than that in the dipole-quadrupole models. This leads to a larger velocity, as discussed below.

The angular velocity $\Omega(t)$ is determined by equating the loss rate of rotational energy
with the luminosity $L$, and the velocity $V(t)$ is determined from the momentum emission $F$. In terms of the mass $M$ and inertial moment $I(=2MR^2/5)$, we have

$$I\dot{\Omega} = -L, \quad M\dot{V} = -F. \quad (2.6)$$

The maximum velocity $\Delta V_\ast$ gained from the initial angular velocity $\Omega_i$ is given with respect to the magnetic moment ratio $Q/(\mu R_s)$:

$$\Delta V_\ast \approx 9.2 \times 10^{-3} \frac{c\gamma}{(\alpha\beta)^{1/2}} \left(\frac{\Omega_i R_s}{c}\right)^2 \approx 120 \left(\frac{P_i}{1\text{ms}}\right)^{-2} \times \frac{\gamma}{(\alpha\beta)^{1/2}} \text{km s}^{-1}, \quad (2.7)$$

where present angular velocity is assumed to be much smaller than initial one $\Omega_i$. The actual maximum depends on the combination of parameters $\gamma/(\alpha\beta)^{1/2}$, which is determined by the magnetic field configuration. By optimal choice, the resultant kick velocity increases up to $\sim 10^3(P_i/1\text{ms})^{-2}$ km s$^{-1}$.

3. Implication

Unlike most magnetic induced kick mechanisms, the electromagnetic rocket mechanism considered in Harrison & Tademaru (1975) and in this paper does not depend on field strength. In our model, the ratio of dipole and quadrupole moments is important. The velocity also depends on the geometrical configuration of the multipole moments, that is, each inclination angle from the spin axis and the angle between the axes of symmetry of the moment. The configuration is quite unknown, and is closely related to the origin of the magnetic field, dynamo or fossil. Nevertheless, interesting results are reported within the mean-field dynamo theory (Bonanno, Urpin & Belvedere 2006): (1) Strong large-scale and weak small-scale fields are generated only in a star with a very short initial period, that is, the Rossy number is small: (2) Maximum strength decreases and small-scale fields become dominant with decrease of the initial period. Thus, magnetars may have an ordered dipole with a strong field, while some pulsars may have rather irregular fields with higher multipoles. Through the superposition of higher multipoles, the pulsars come to have a larger radiation recoil velocity than magnetars.

References

A pulsar census of the Local Group

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Abstract. We carried out a search for pulsars in nearby galaxies with the GBT and Arecibo radio telescopes at 820 and 327 MHz, correspondingly. Currently, the Magellanic Clouds are the only galaxies except for Milky Way known to harbor radio pulsars, with a total of 20 pulsars being discovered there to date. Discovery of pulsars in other galaxies can be used to trace the history of massive star formation and would allow to probe the intermediate intergalactic medium. We selected 22 galaxies of the Local Group at high galactic latitudes, $|b| > 26$ deg, with most of them being dwarf spheroidals with old star population. This makes them promising targets to search for giant pulses from recycled millisecond pulsars. Both single-pulse and periodicity searches were performed for trial dispersion measures up to 1000. No extragalactic pulsars are found in half of the selected targets processed so far. I will give the overview of our targeted searches, present potential candidates and discuss the obtained results.
Tracking dispersion measure variations of timing array pulsars with the GMRT

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Abstract. We present the results from nearly three years of monitoring of the variations in dispersion measure (DM) along the line-of-sight to 11 millisecond pulsars using the Giant Metrewave Radio Telescope (GMRT). These results demonstrate accuracies of single epoch DM estimates of the order of $5 \times 10^{-4}$ cm$^{-3}$ pc. A preliminary comparison with the Parkes Pulsar Timing Array (PPTA) data shows that the measured DM fluctuations are comparable. We show effects of DM variations due to the solar wind and solar corona and compare with the existing models.

Keywords. (stars:) pulsars: general, ISM: general, Sun: corona

1. Introduction

Dispersion measure quantifies the integrated dispersive effect of the plasma between the pulsar and the observing telescope, on the propagating broadband pulsar signal. In general, it varies with time due to reasons such as the transverse motion of pulsar sampling different lines of sight (LOS) through inhomogeneous and turbulent interstellar medium (ISM), solar wind and solar corona, plasma density changes in the binary orbit and drifting wisps of ionized gas in supernova shell. For Pulsar Timing Arrays (PTAs), which aim for a final accuracy of 100 ns or better at L band, DM variations as small as $\sim 5 \times 10^{-5}$ cm$^{-3}$ pc need to be corrected for. Meanwhile, the timing accuracies currently achieved for most of the PPTA pulsars are still of the order of a µs and above (Manchester 2011) and therefore DM corrections could improve these. As indicated from the observations by Backer et al. (1993), Hobbs et al. (2004), later from analytical derivation, for a turbulent ISM, $|d(DM)/dt| \approx 0.0002 \sqrt{DM}$ cm$^{-3}$ pc yr$^{-1}$, which implies significant change over a period of a few days to a week for a typical DM of a few tens of cm$^{-3}$ pc. The GMRT, using its low frequency capability, can provide more accurate DM measurements by taking advantage of the inverse-square law dependency of the delay on the observing frequency, as has been demonstrated by Ahuja et al. (2005), who had achieved an accuracy of up to $5 \times 10^{-3}$ cm$^{-3}$ pc for long period pulsars.

2. Observations and analysis

A program was initiated at the GMRT, in Nov 2009, to carry out roughly bi-weekly simultaneous dual-frequency observations at 325 and 610 MHz for 11 millisecond pulsars
Table 1. Summary of the DM measurements for nine of the MSPs. The catalogue period is in ms, DM_{cat} and < DM > are in cm^{-3} pc, rms_{DM} and < error > are in 10^{-4} cm^{-3} pc. The last four columns give the mean of DM, rms of DM, the mean absolute error of DM over all the epochs and the equivalent TOA error at L band (corresponding to the rms) in $\mu$s.

<table>
<thead>
<tr>
<th>PSR</th>
<th>$P_{\text{cat}}$</th>
<th>$DM_{\text{cat}}$</th>
<th>&lt; DM &gt;</th>
<th>rms_{DM}</th>
<th>&lt; error &gt;</th>
<th>$\Delta$TOA_l</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2145-0750</td>
<td>16.0524</td>
<td>8.9977</td>
<td>9.0066</td>
<td>3.10</td>
<td>0.90</td>
<td>0.65</td>
</tr>
<tr>
<td>J1744-1134</td>
<td>4.07454</td>
<td>3.1390</td>
<td>3.1396</td>
<td>2.30</td>
<td>1.07</td>
<td>0.53</td>
</tr>
<tr>
<td>J1730-2304</td>
<td>8.12279</td>
<td>9.6170</td>
<td>9.6275</td>
<td>5.00</td>
<td>1.13</td>
<td>1.06</td>
</tr>
<tr>
<td>J1713-0747</td>
<td>4.57013</td>
<td>15.993</td>
<td>15.993</td>
<td>5.20</td>
<td>1.17</td>
<td>1.09</td>
</tr>
<tr>
<td>J1909-3744</td>
<td>2.94710</td>
<td>10.393</td>
<td>10.394</td>
<td>2.60</td>
<td>1.30</td>
<td>0.55</td>
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<tr>
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<td>4.62164</td>
<td>62.412</td>
<td>62.424</td>
<td>14.9</td>
<td>1.37</td>
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</tr>
<tr>
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<td>6.75745</td>
<td>2.6447</td>
<td>2.6491</td>
<td>4.28</td>
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</tr>
<tr>
<td>J1022+1001</td>
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<td>10.239</td>
<td>5.70</td>
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<td>1.20</td>
</tr>
<tr>
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<td>38.779</td>
<td>38.795</td>
<td>5.00</td>
<td>2.50</td>
<td>1.05</td>
</tr>
</tbody>
</table>

(MSPs), primarily to track the DM variations accurately and study their effects on timing accuracy as well as for studying DM variations due to the solar corona and the solar wind. The observations used the GMRT software back-end (Roy et al. 2010) in the simultaneous dual-frequency phased array mode, giving total intensity time-series from 512 channels over 32 MHz of bandwidth at each frequency. In this mode the data streams from the two frequencies are locked to each other without any instrumental delay, allowing accurate DM estimates without requiring absolute timing measurements. The data were incoherently dedispersed and folded using a Doppler corrected period. The delay was computed using the peak of the cross-correlation between the profiles at the two frequencies. The DM was computed as

$$DM = \left(\frac{\Delta t}{K}\right) \times \frac{1}{\nu_1^2 - \nu_2^2} \text{ cm}^{-3} \text{ pc},$$

where $K$, called dispersion constant, is equal to $4.1488080 \pm 30 \times 10^3 \text{ MHz}^2 \text{ cm}^{-3} \text{ pc}^{-1} \text{ s}$. Errors were estimated by propagating the off-pulse noise of the two profiles to estimate the rms error of the measured delay.

3. Results, conclusions & future goals

Significant DM variations are detected (Table 1) for all the pulsars, with accuracies of $5 \times 10^{-4} \text{ cm}^{-3} \text{ pc}$ achieved for most of them. For most pulsars, the rms DM variation is comparable to that seen in the PPTA data and also to the reported value from You et al. (2007a). The DM variations seem to show significant correlation with the Parkes data for four MSPs (Figure 1).

The effects of solar corona are clearly detected in the case of low ecliptic latitude pulsars (Figure 2), even though many of our data points, up to 25° from the Sun, seem to disagree with the predictions based on the two-state solar wind model of You et al. (2007b), indicating possibilities for further refinements of the model including effects of special events like coronal mass ejections (CMEs).

Two-state jumps in PSR J1022+1001’s DM variation (Figure 2) are found to be due to small, but quite well defined profile shape changes, akin to the well known mode changing phenomenon seen in some pulsars. Further comparisons and studies (e.g. ISM structure function analysis) will be possible in future as our data extend to longer time spans.

References

Figure 1. Comparison of DM time-series from the GMRT and Parkes, for PSRs J1909-3744 & J1730-2304.

Figure 2. Left: DM variations for PSR J1730-2304, showing large increases around the times of closest approach to the Sun. Right: Consolidated DM variation as a function of elongation from the Sun from data for all pulsars and comparison with TEMPO1 (red) & TEMPO2 (green).

Figure 3. Two-state DM fluctuation for PSR J1022+1001.

Abstract. The study of dense matter at ultra-high density has a very long history, which is meaningful for us to understand not only cosmic events in extreme circumstances but also fundamental laws of physics. In compact stars at only a few nuclear densities but low temperature, quarks could be interacting strongly with each other. That might produce quarks grouped in clusters, although the hypothetical quark-clusters in cold dense matter have not been confirmed due to the lack of both theoretical and experimental evidence. A so-called $H$-cluster matter is proposed in this paper as the nature of dense matter in reality. Motivated by recent lattice QCD simulations of the $H$-dibaryons (with structure $uuddss$), we are therefore considering here a possible kind of quark-clusters, $H$-clusters, that could emerge inside compact stars during their initial cooling, as the dominant components inside (the degree of freedom could then be $H$-clusters there). We study the stars composed of $H$-clusters, i.e., $H$-cluster stars, and derive the dependence of their maximum mass on the in-medium stiffening effect, showing that the maximum mass could be well above $2\ M_\odot$ as observed and that the resultant mass-radius relation fits the measurement of the rapid burster under reasonable parameters. Besides a general understanding of different manifestations of compact stars, we expect further observational and experimental tests for the $H$-cluster stars in the future.

Keywords. pulsars: general, stars: neutron, equation of state

1. Introduction

Compact objects, especially at density as high as nuclear matter density, are recognized by astronomers and physicists as a unique window on the relations between fundamental particle physics and astrophysics. Above the saturated nuclear matter density, $\rho_0$, the state of matter is still far from certain, whereas it is essential for the exploration of the nature of pulsars. In cold quark matter at realistic baryon densities of compact stars ($\rho \sim 2 - 10\rho_0$), the energy scale is far from the region where the asymptotic freedom approximation could apply. In this case, the interaction energy between quarks could be comparable to the Fermi energy, so that the the ground state of realistic quark matter might not be that of Fermi gas (see a discussion given in Xu 2003, 2010). It is then reasonable to infer that quarks could be coupled strongly also in the interior of quark stars, which could make quarks condensate in position space, to form quark clusters. The resulting quark stars could then be actually “quark-cluster stars”.

Quark clusters may be analogized to hadrons. In our previous work about the quark-clusters stars, we first proposed a general form of equation of state, the polytropic model, to describe the clustering quark matter (Lai & Xu 2009a). Then we took the number of quarks inside each quark-cluster $N_q$ as a free parameter, applying the Lennard-Jones interaction to model the inter-cluster potential (Lai & Xu 2009b, 2011). Here we specify the quark-clusters, under the light flavor symmetry, to be $H$-clusters (Lai et al. 2011).
2. In-medium stiffening

We suppose that the in-medium stiffening, i.e. the so called Brown-Rho scaling (Brown et al. 1991, Brown & Rho 2004), holds for nucleons, mesons and H-dibaryons, with the same coefficient of scaling $\alpha_{BR}$,

$$m_n^*/m_n = m_M^*/m_M = 1 - \alpha_{BR} \frac{n_n}{n_0}, \quad m_H^*/m_H = 1 - \alpha_{BR} \frac{n}{n_0},$$  \hspace{1cm} (2.1)

where $n_0$ denotes the number density of saturated nuclear matter, $n_n$ and $n$ denote the nucleon number density and H-dibaryon number density, $m_n$ and $m_M$ denote the mass of neutrons and mesons, and the masses with and without asterisks stand for in-medium values and free-space values respectively. The decreasing of the mass of H-dibaryons with increasing densities could be equivalent to the increasing of binding energy of H-dibaryons, which makes H-clusters to be more stable.

3. Equation of state and mass-radius curves of H-cluster stars

The interaction between H-clusters has been studied under the Yukawa potential with $\sigma$ and $\omega$ coupling (Faessler et al. 1997),

$$V(r) = \frac{g_{\omega_H}^2}{4\pi} \frac{e^{-m_{\omega_H}^* r}}{r} - \frac{g_{\sigma_H}^2}{4\pi} \frac{e^{-m_{\sigma_H}^* r}}{r},$$  \hspace{1cm} (3.1)

where $g_{\omega_H}$ and $g_{\sigma_H}$ are the coupling constants of H-clusters and meson fields. Assuming the localized H-clusters form the simple-cubic structure, we can get the interaction energy density $\epsilon_I \propto n \cdot V$, and then we can get the pressure $P = n^2 \frac{d}{dn} (\frac{\epsilon_I}{n})$, where the total energy density is $\epsilon = \epsilon_I + m_{\gamma}^* \cdot n$. By this way, we can derive the equation of state.

From the equation of state we can get the mass $M$ and radius $R$ of an H-cluster star, from the hydrostatic equilibrium condition in general relativity. The results are shown in Figure 1. Our results are consistent with both the mass of a binary millisecond pulsar PSR J1614-2230 (Demorest et al. 2010) and the mass-radius measurement of the neutron star in the Rapid Burster MXB 1730-335 (at least at 2 $\sigma$; Sala et al. 2012).

4. Conclusions

We propose that, if the light flavor symmetry is restored, the strong interaction between quarks inside compact stars could render quarks grouped into a special kind of quark-clusters, H-clusters, leading the formation of H-cluster stars. The equation of state of H-cluster stars is derived by assuming the Yukawa form of H-H interaction under meson-exchanges, and the in-medium effect from Brown-Rho scaling law of meson-masses is also taken into account. H-cluster stars are self-bound objects, and they could be very low masses as well as very high masses (well above $2M_\odot$).

Finally, we would clarify two questions and answers, which should be beneficial to make sense about the conclusions presented in this paper. (1) Why does not an H-particle on the surface decay into nucleons? The reason could be similar to that why a neutron does not decay into proton in a stable nucleus. Landau (1938) demonstrated that significant gravitational energy would be released if neutrons are concentrated in the core of a star. It is now recognized, however, that fundamental color interaction is more effective and stronger than gravity to confine nucleons. The equality condition of chemical potentials at the boundary between two phases applies for gravity-confined stars (Landau 1938), but may not for self-bound objects by strong interaction. (2) Why can hardly normal matter be converted into more stable H-cluster matter in reality? We know $^{56}$Fe is most stable.
nucleus, but it needs substantial thermal kinematic energy to make nuclear fusion of light nuclei in order to penetrate the Coulomb barrier. Strong gravity of an evolved massive star dominates the electromagnetic force, compressing baryonic matter into quark-cluster matter in astrophysics. This is expensive and rare.

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References

A data analysis library for gravitational wave detection

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Abstract. One of the main goals of Pulsar Timing Arrays (PTAs) is the direct detection of gravitational waves (GWs). A first detection will be a major leap for astronomy and substantial effort is currently going into timing as many pulsars as possible, with the highest possible accuracy. As part of the individual PTA projects, several groups are developing data analysis methods for the final stage of a gravitational-waves search pipeline: the analysis of the timing residuals. Here we report the progress of on-going work to develop, within a Bayesian framework, a comprehensive and user friendly analysis library to search for gravitational waves in PTA data.

Keywords. pulsars: general, gravitational waves, methods: data analysis

1. Introduction

High precision timing of millisecond pulsars holds great promise for the detection of gravitational waves (GWs) in the $10^{-9}$ – $10^{-7}$ Hz frequency range, which includes the inspiral regime of Super Massive Black Holes Binaries (SMBHBs). GWs affect the time of arrival of the radio pulses coming from pulsars in the PTA (see Estabrook & Wahlquist 1975, Sazhin 1978, Detweiler 1979). The GWs perturb the propagation of the observed radio emission in such a way that the arrival time of the pulses only depends on the metric perturbation at the pulsar at the moment of emission (the “pulsar term”), and the metric perturbation at the Earth at the point of reception (the “Earth term”). Due to the continuous monitoring of many pulsars, the Earth term is correlated between every pulsar pair in a unique way described by General Relativity. Hellings & Downs (1983) have shown what these correlations have for an isotropic stochastic background of GWs, such as the one generated by an unresolved cosmic population of SMBHBs. The spectral density of this signal follows a power law (see Maggiore 2000, Phinney 2001) and is defined in terms of its characteristic strain:

\begin{equation}
    h_c = A \left( \frac{f}{y_p^{-1}} \right)^\alpha,
\end{equation}

where $A$ is the signal amplitude, $f$ its frequency and $\alpha$ the spectral index.

Besides the stochastic GWB, there are other possible signals in the observations
which one should consider: GWs from individually resolvable sources (Sesana & Vecchio 2010, Mingarelli et al. 2012, Ellis et al. 2012), cosmic strings (Sanidas et al. 2012), GW bursts (Pitkin 2012), imperfections in terrestrial time standards (Hobbs et al. 2012), and dispersion measure variations. New methods to look for these signals are continuously being developed, but to date there is no easy to use open data analysis pipeline specifically designed to combine all these in a single pipeline. The purpose of this work is to provide such a versatile and modular pipeline for the pulsar timing community.

2. Example

An example of general pulsar timing analysis is the correct treatment of time-correlated stochastic signals, like red timing noise, in pulsar timing data. In solving for the timing model parameters, a lot of the timing noise is absorbed in the fitting procedure. Several consistent methods now exist to treat red timing noise: among them the Cholesky method of Coles et al. (2011), and the Bayesian method of Haasteren et al. (2009, 2012). In the panel above the reconstruction of some simulated low frequency timing noise is presented for the Cholesky method, and the maximum likelihood (ML)

![Figure 1. Different reconstructions of injected low frequency noise. The bottom panel is the input of the residuals without any pre-processing (input). The second lowest shows the injected form of the residuals containing the low frequency noise (injected). The top panel shows the reconstruction with the Maximum likelihood method (Max-Lik), the second highest one shows a reconstruction using the Cholesky method (Cholesky). For the reconstructions, we have plotted the 1σ intervals for the pulse frequency; the lowest frequency timing model parameter. For the Maximum likelihood estimator, the injected signal seems to lie more within this interval.](image)
method of van Haasteren (2012). Correct treatment of the timing noise, especially for the low-frequency behaviour, is essential for gravitational-wave detection. Both methods will be easily accessible in the new data analysis library.

3. Structure of the data analysis process
The goal of our software library, developed in python and C, is to be as user-friendly as possible. At the moment, no uniform pipeline or software library is publicly available for this kind of analysis. The purpose of this work is to be able to combine different models and different algorithms in the simplest way.

The key element of such a pipeline is the likelihood evaluator, which implements the likelihood function. The likelihood evaluator will be implemented as part of a modular library, where each of the modules can be easily replaced with an alternative. Different samplers, and signal models can therefore be easily combined without having to make changes in the library. Standard modules will be provided for the treatment of typical analysis cases, including GW(B) detection, red noise estimation, and dispersion measure variation correction. Future models will include GWs from single sources, bursts and cosmic strings.

4. Conclusion
We present a new library, still under construction, designed to become a universal tool for the analysis of pulsar timing data. The library has a special focus on pulsar timing array science and GW detection, but will also contain useful methods for pulsar timing in general. Typical problems that this library is especially well-suited for are pulsar timing data analysis in the presence of strong low-frequency noise and GW detection. Independent library modules can be easily combined and replaced, which allows different types of analysis to be done without having to change any code. Such modules include, but are not limited to, the modules implementing Markov Chain Monte Carlo samplers, and modules describing the GW signal model in the likelihood function. We will provide standard modules for many common data analysis problems, so that a typical analysis can be done “out of the box”.

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Modelling X-ray Pulse Profiles of Millisecond Pulsars

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Abstract.
The modelling of X-ray pulse profiles from accreting millisecond pulsars is a way to infer masses and radii of neutron stars. We briefly describe how a pulse shape encodes information on the mass and radius, but also depends on other parameters such as hot spot location and observer viewing angle. A numerical model that we have developed is then described. The model includes light bending, time-delay effects, and Doppler effects for photons. The model accounts for oblateness of the neutron star, caused by the rapid rotation, and for scattered light from the surface of the accretion disk. The millisecond pulsar SAX J1808-3658 has multiple observations taken during different outbursts. The observed pulse shapes vary greatly, and it is a challenging test to fit the different observations. Some of the latest results are given.

Keywords. dense matter, equation of state, gravitational lensing, stars: neutron

The modelling of X-ray pulse profiles from accreting millisecond pulsars, is one method used to infer masses and radii of neutron stars, although it has not reached the accuracy obtained for the pulse profile model of Hercules X-1 (Leahy, 2004). For a summary of methods see the review paper by Lattimer & Prakash (2007). Gravity plays a strong role in the propagation of light from the neutron star to observer, as well as on the structure of the neutron star itself. Thus light-bending must be included in any model of observations of neutron stars. Because of the rapid rotation of millisecond (ms) pulsars, Doppler effects (boosting and aberration), which depend on emitter velocity, affect the observed X-ray pulse shapes. As a consequence of light bending and Doppler effects, pulse shapes carry useful information on the mass, radius and surface shape of the neutron star.

The numerical model that we have developed includes light bending and time-delay effects, as well as Doppler effects for photons. This model is described in detail in a series of papers (listed below). The model also accounts for oblateness of the neutron star, caused by the rapid rotation, and includes a scattered light component from the surface of the accretion disk.

The calculation of pulse shapes is done by ray tracing, using the geodesic equations of general relativity (GR). Full calculations use the numerical GR metrics for rotating neutron stars. Expansion of the geodesic equations in the metric for a rotating neutron star yields redshift and Doppler factors Cadeau et al. (2007). Time-delays are important for pulse shapes, but the difference between Schwarzschild and Kerr metrics are not im-
portant Cadeau et al. (2005): both have similar (but small) differences from the correct neutron star metric. Omitting the fact that rapid rotation causes the neutron star to have an oblate shape produces large errors in the pulse shapes (for spin frequencies $\lesssim 300\text{Hz}$; Cadeau et al. 2007). An approximation method to the full GR calculation was presented by Morsink et al. (2007). This was essential as a practical method calculating pulse shapes because the full GR calculation is too compute-intensive to be used in pulse shape fitting programs. This approximate method is called the oblate-Schwarzschild approximation. It was applied to SAX J1808-3658 by Leahy et al. (2008).

Including data from two or more different observations of the same millisecond X-ray pulsar is very useful to distinguish fixed parameters (mass, radius and observer viewing angle) from variable parameters (hot spot location size and emission properties). Joint fits of more than one pulse shape was first done using data on the millisecond X-ray pulsar XTE J1814-338 by Leahy et al. (2009). It was then extended to observed pulse profiles of SAX J1808-3658 by Morsink & Leahy (2011). This work also introduced a scattered light component, for X-rays scattered from the neutron star hot spot off the accretion disk. This was needed in order to provide satisfactory models for the observed pulse shapes. Leahy et al. (2011) applied the oblate Schwarzschild model with scattered light with a joint fit to pulse profiles from 3 epochs from XTE J1807-294.

The millisecond pulsar SAX J1808-3658 has multiple observations taken during different outbursts as described by Hartman et al. (2008). It is a challenging test to fit the different observations, in large part because of the large number of free parameters needed to describe the time-variable emitting region, the neutron star and observer geometry. Details will be presented in a future publication.

Figure 1 compares model fits with and without scattered light. The 3-4 keV band has a significant contribution from a blackbody spectral component with isotropic phase function; the 9-20 keV band is dominated by the power-law spectral component with an electron scattering phase function. The model with disk-scattered light is a significantly better fit to the observed pulse profile. Figure 2 shows the best fit values of mass and
radius for different pairs of 2-epoch fits, and the 3 sigma allowed region for the 2-epoch fit using 1998b4 and 2002b3 data sets. We have carried out 3-epoch fits which yield consistent best fit mass and radius and also a significantly smaller 3 sigma allowed region. Next is planned improvements in the fitting algorithm and then results from joint 4-epoch fits.

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Figure 2. Best fit values of M and R for the labelled pairs of pulse profiles from SAX J1808-3658 (solid points) plus the 3-sigma limits on M and R for the 1998b4-2002b3 joint pulse shape fit.
Broadband spectral investigations of SGR J1550−5418 bursts

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Abstract.
We present the results of our broadband (0.5−200 keV) spectral analysis of 42 SGR J1550−5418 bursts simultaneously detected with the Swift/X-ray Telescope (XRT) and the Fermi/Gamma-ray Burst Monitor (GBM), during the 2009 January active episode of the source. We find that, on average, the burst spectra are better described with two blackbody functions than with the Comptonized model. Thus, our joint XRT/GBM analysis clearly shows for the first time that the SGR J1550−5418 burst spectra might naturally be expected to exhibit a more truly thermalized character, such as a two-blackbody or even a multi-blackbody signal. We also studied the spin phase of the XRT burst emission, which indicate that the burst emitting sites on the neutron star need not to be co-located with hot spots emitting the bulk of the persistent X-ray emission and the surface magnetic field of SGR J1550−5418 is likely non-uniform over the emission zone.

Keywords. stars: neutron, pulsars: individual (SGR J1550−5418, 1E 1547.0−5408, PSR J1550−5418), X-rays: bursts

1. Introduction
Magnetars are isolated neutron stars possessing extreme magnetic fields over $10^{14}$ G, observed as Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs). Besides being bright X-ray sources, SGRs and AXPs emit intense bursts in hard X-rays / soft γ-rays on a highly unpredictable frequency. A typical burst from magnetars lasts for $\sim 100$ ms with the peak luminosity of $10^{38} \sim 10^{41}$ erg s$^{-1}$. Its spectrum is equally well described with a Comptonized model (COMPT) or the sum of two blackbody functions (BB+BB) in 8 − 200 keV (Lin et al. 2011, van der Horst et al. 2012). These two models, which have very different physical origin (thermal or non-thermal) cannot be distinguished in the GBM energy range. However, they have large dispersion in the lower energy band below 10 keV, making the model discrimination possible.

2. Sample selection
The unique spectral and temporal capabilities of the XRT Windowed Timing mode have allowed us to extend the GBM spectral coverage down to the X-ray domain (0.5 – 10 keV). We found 42 SGR J1550-5418 bursts simultaneously detected with the Swift/XRT and the Fermi/GBM during its 2009 January active episode. Figure 1 exhibits the lightcurve and the spectrum of one of the simultaneous events.

3. Results
We fit all 42 simultaneously bursts with both COMPT and BB+BB models using only GBM data and joint XRT-GBM data. On average, BB+BB model fits better than
COMPT. First of all, BB+BB model fits provide less systematic residuals (see joint fit spectra in Figure 1) and smaller average reduced \( \chi^2 \) values. Secondly, the mean value of the COMPT index distribution from joint analysis is \(-0.58 \pm 0.09\), much harder than GBM data only result \((-0.87 \pm 0.05)\), as shown in the left panel of Figure 2. This indicates that GBM data only fits with COMPT model may over estimate the low energy emission. Finally, since the COMPT model has one less parameter than the BB+BB function and they are not nested, we performed extensive simulations for each of the 42 bursts to determine the significance of the model preference (see Lin et al. 2012 for more details).

We selected the model with smaller \( \chi^2 \) as seed model and simulate 10000 spectra with the seed model. Then we fit all simulated spectra with both COMPT and BB+BB models. We then calculated the probability (P) of the simulated spectra have a smaller \( \chi^2 \) fit with the seed model. We defined the seed model significantly better than the other one in case of \( P > 90\% \). For 31 bursts out of 42 the BB+BB model fits significantly better than the COMPT. The bright bursts in our sample prefer the BB+BB model. The right panel of Figure 2 presents the relation between P and the total counts of bursts in 8 – 200 keV band.

We further studied the properties of 31 BB+BB bursts. The temperature of two blackbody components are \( 4.4 \pm 0.2 \text{ keV} \) and \( 16.0 \pm 0.4 \text{ keV} \), consistent with those from other magnetar bursts. The energy emitted from hot blackbody is twice the energy from the cool one. Assuming the distance to SGR J1550 – 5418 as 5 kpc, we calculate the emission
area for each blackbody component. The correlation between the emission area and the temperature through cool and hot component is similar to that of a single blackbody with a certain flux (Figure 3 left panel).

To better understand the BB+BB behavior and uncover its relation with the spin properties of SGR J1550–5418, we investigated the phase characteristics of the 31 BB+BB bursts (see the right panel of Figure 3). We selected all XRT counts collected during 31 burst intervals and calculated the spin phase for each burst count using the appropriate spin ephemeris of epoch (MJD) 54854 as reported by Dib et al. (2012). To ensure that the distribution is not dominated by the excessive counts of the brightest bursts, we also calculated the probability density for each phase bin, which is the average of the normalized (by total counts) phase distributions for all bursts. We find that the probability distribution of the burst counts is not uniform over the spin phase of SGR J1550–5418 and the deviation from the mean probability is significant (RMS = 0.021 ± 0.001). Compared with the persistent emission phase profile obtained using contemporaneous XMM observations, the phase probability density function is marginally anti-correlated with the persistent emission phase profile in our burst sample. This indicates that the burst emission regions on the neutron star surface are not necessarily associated with the site persistently emitting in X-rays (typically a BB with a temperature of 0.5 keV). This is in agreement with the crustal fracturing mechanism for SGR bursts (Thompson & Duncan 1995) as any portion of the solid crust can fracture if the magnetic stress built up is near the threshold to rupture. We also find that the burst probability of some spin phases in SGR J1550–5418 is higher. This could be attributed to a non-uniform surface magnetic field, with some regions having larger magnetic stresses than others.

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Profile stability and timing precision limit of millisecond pulsars

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Abstract. Millisecond pulsars are shown to have highly regular rotations and stable profiles, which enables the utilisation of them as accurate clocks. In this talk, I will present the latest studies on profile stability of several millisecond pulsars. I will focus on single pulse stability and its influence on the shape and phase of integrated profiles achieved on short timescales. It will be shown that the single pulse instability seems to be a source dependent issue, and they would influence differently on timing precision of the pulsar. The understanding of profile stability is essential in determining the timing precision limit and the optimal timing scheme with the future radio telescopes.
The missing compact star of SN1987A: a solid quark star?

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Abstract. To investigate the missing compact star of Supernova 1987A, we analyzed the cooling and heating processes of a possible compact star based on the upper limit of observational X-ray luminosity. From the cooling process, we found that a solid quark-cluster star (SQS), having a stiffer equation of state than that of a conventional liquid quark star, has a heat capacity much smaller than a neutron star. The SQS can cool down quickly, naturally explaining the non-detection of a point source in X-ray wavelengths. On the other hand, we considered the heating processes due to magnetospheric activity and possible accretion and obtained some constraints on the parameters of a possible pulsar. Therefore, we concluded that a SQS can explain the observational limit in a confident parameter space. As a possible central compact object, the pulsar parameter constraints can be tested for SN1987A with advanced, future facilities.

Keywords. pulsar: general – elementary particles – supernovae – star: neutron

1. Introduction

The missing compact star of Supernova 1987A is puzzling, mainly because of three factors: First, the neutrino burst from SN1987A indicates the forming of a neutron star; Second, the X-ray luminosity of a cooling neutron star is higher than the observational upper limit at 1 keV (McCray 2007), thus the implied neutron star is expected to be detectable; and third, multi-wavelength observations did not find any point source or pulses at the position of SN1987A. Therefore, there must be something wrong or unusual.

There are two existing explanations for this puzzle: 1) The neutron star has transformed to a black hole via accretion from fall-back material; 2) It is a normal quark star, which cools very fast, that has luminosity lower than the observational limit (Chan et al. 2009). We note that both hypotheses have trouble explaining a 2 solar mass neutron star (Demorest et al. 2010), which means the maximum mass is larger than ever thought. The normal quark star is almost ruled out since its equation of state is too soft to reach 2 solar masses. And a black hole should be more difficult to form because it would need to accrete more fall-back material to exceed the maximum mass.

We propose that the compact star in SN1987A is a solid quark cluster star (SQS). The SQS has very small heat capacity thus cools faster than neutron star and has smaller X-ray luminosity than the observational limit, and it has stiff equation of state that can have maximum mass larger than 2 solar mass (Lai & Xu 2009).
2. Cooling of quark cluster star

2.1. Heat capacity

The heat capacity of quark cluster star is composed by the contributions of lattice structure $C_{\text{SQS}}^l$ and electrons $C_{\text{SQS}}^e$, i.e. $C_{\text{SQS}} = C_{\text{SQS}}^l + C_{\text{SQS}}^e$ (Yu & Xu 2011), where $C_{\text{SQS}}^l$ is proportional to $T^3$, and $C_{\text{SQS}}^e$ is proportional to $T$. The heat capacity is dominated by electrons when the temperature is lower than $\sim 10^{10}$K. The contribution of electrons is $C_{\text{SQS}}^e \simeq 3.5 \times 10^{37} (Y M_1)^{2/3} R_6 T_9$ erg K$^{-1}$ where $Y \sim 10^{-5}$ is the electron fraction.

2.2. Cooling curve

The heat energy could emit via neutrino radiation, color superconductivity related photon emission and bremsstrahlung. Figure 1 shows the cooling curve of a quark cluster star via only Bremsstrahlung (BR), compared with black-body emission. It shows that even if it cools only via bremsstrahlung the luminosity is lower than the observational limit at the age of 20 years.

3. Restrict parameters via heating

The heating luminosity should also be lower that the limit, thus it can be used to restrict the compact star’s parameters.

3.1. Heating from magnetosphere

The rotational energy lost rate is related to the magnetic field and rotation frequency $\dot{E} = -\frac{2}{3} \mu^2 \Omega^4$. The thermal X-ray luminosity is proportional to $\dot{E}$, i.e. $L_{\text{bol}}^\infty = a \dot{E}$, where $a \sim 10^{-3}$ (Yu & Xu 2011). The red lines in two panels of figure 2 are obtained with $a = 10^{-4}, 10^{-3}$ and $10^{-2}$. The areas left to the lines should be ruled out.

![Figure 1. The cooling curves of SQSs with bremsstrahlung (BR) (Caron & Zhitnitsky 2009) and black-body radiation (BB). Neutrino radiation and color superconductivity related photon emission are not considered. The observational upper limit is indicated as a horizontal dotted line. It shows that the cooling luminosity of a SQS could be smaller than $10^{34}$ ergs s$^{-1}$ about 20 years after its birth even it cools down by bremsstrahlung emission. Here we take the stellar mass $M = M_1 M_\odot$ and the number ratio of electron to baryon as $Y$.](image)
Figure 2. Constraints on parameters of the possible compact object in SN1987A via magneto-sphere action heating (upper-left three lines) and fall back disk accretion heating (lower-right three lines). Left panel: $M_1 = 2$ and $b = 0.9$, $a = 10^{-4}$ for red dash-dotted line, $a = 10^{-3}$ for red dashed line, $a = 10^{-2}$ for red solid line, $\dot{M} = 10^{18}$ erg s$^{-1}$ for blue solid line, $\dot{M} = 10^{16}$ erg s$^{-1}$ for blue dashed line and $\dot{M} = 10^{14}$ erg s$^{-1}$ for blue dash-dotted line. Right panel: Same as the left but $M_1 = 1$.

3.2. Heating from accretion

If there is a disk around, it should not be in accretion phase which usually has very large luminosity. Thus $r_m > r_br_r$, yielding $\mu_{30} > 0.074 b_{7/4} M_{15}^{5/6} \dot{M}_{16}^{1/2} P_7^{7/6}$. The blue lines in two panels of the figure 2 are obtained with $\dot{M} = 10^{18}$ erg s$^{-1}$ for blue solid line, $\dot{M} = 10^{16}$ erg s$^{-1}$ for blue dashed line and $\dot{M} = 10^{14}$ erg s$^{-1}$ for blue dash-dotted line.

4. Summary

Based on the foregoing analysis and calculation results, we conclude that:

1) A solid quark star with normal parameters is compatible with the non-detection in SN1987A. A low-mass quark cluster star has a wider parameter space than a more massive one;

2) If the surround dust is opacity in X-ray band, the parameter constraints become relaxed. The parameter space of a solid quark star is wider than that of a neutron star;

3) The parameter constraints are model independent.

As a possible central compact object, the parameters constrained for the pulsar can be tested for SN1987A with advanced, future facilities.

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Relativistic Cowling approximation for fluid oscillation modes of color superconducting self-bound stars

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Abstract. The investigation of the quasi-normal modes of oscillation of compact stars can reveal much information about their equation of state and internal structure mainly through the analysis of the expected emission of gravitational waves. In this work we study non-radial oscillation modes of strange stars consisting of color superconducting quark matter. We focus on the fundamental and pressure oscillation modes within the frame of the Cowling approximation. We discuss the observable features that may allow a differentiation among hadronic stars, strange stars, and strange stars with color superconductivity.
New observations of the Geminga pulsar at low radio frequencies

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Abstract. New evidence for the detection of Geminga at three low frequencies is presented. The observations were carried out on two sensitive transit radio telescopes in the range 42-112 MHz. We used three new digital receivers to detect the pulses and to obtain dynamic spectra. The exact value of the dispersion measure has been calculated.

Keywords. Pulsars.

1. Introduction
The famous neutron star Geminga was the first astronomical object discovered through its γ-ray emission, in 1975 (Kniffen et al. 1975). The detection of coherent pulsation with a period of 237 ms in X-ray emission and the pulsed γ- radiation were next reported in 1992 (Halpern & Holt 1992, Bertsch et al. 1992). Three groups reported the detection of pulsed radio emission from Geminga at frequency 102.5 MHz (Malofeev & Malov 1997; Kuzmin & Losovsky 1997; Shitov & Pugachev 1998). One group confirmed the pulsed radio emission at the same frequency of 103 MHz (Vats et al. 1999). Recently weak continuum radio emission has been detected at the frequency 4.8 GHz (Pellizzoni et al. 2011).

2. Observations and results
The observations were carried out on two sensitive transit radio telescopes in Pushchino in the range 42-112 MHz. They have been made at 111.5 MHz using Large Phase Array (LPA) antenna, with is a transit phased array comprising 16384 dipoles and covering an area of 18 acres. Its operating frequency is 111.5 ± 1.5 MHz and the telescope is a sensitive instrument with an effective area of ≃ 3·10^4 m^2. The high-sensitivity DKR-1000 (EastWest arm), which operates at 30-110 MHz, has an effective area of ≃ 7000 m^2 and an observing session duration of 15 m/cos δ. New series of observations were obtained using a unique set of digital, multi-channel receivers designed for pulsar observations, which came into use in 2006-09. The width of the operational frequency band is 2.5 MHz, which is separated by the FFT into 512 spectral channels with widths of 4.88 kHz each.

The reduction programmes implement several techniques for removing interference, using several criteria for distinguishing false pulses from real signals (for details see Malofeev et al. 2012).

In the beginning of this year new observations in Pushchino showed the evidence for the detection of Geminga at three low frequencies during two months (January-February of 2012) in a few sets of observations. Here, we present the results for three days 19—21 of January. To check for the presence of the weak pulsar signal and to raise the
**Figure 1.** Example of a pulse profile (upper) and a dynamical spectrum (lower) of Geminga at 111 MHz, obtained by summing 36 selected groups (triple periods) on the 20.01.12. The horizontal axis is in samples of the triple period of the pulsar. The dispersion track is marked by arrows.

**Figure 2.** Examples of an individual pulse profiles of Geminga at 111 MHz on the 20.01.12. The horizontal axis is in samples of the triple period of the pulsar. The phases of pulses are marked by arrows.
Figure 3. The central panel shows events with $S/N > 2.5$ at different DM versus number at pulse (time). DM with larger circles denoting stronger signal. The left panel shows the histogram of the number of events versus DM. The right panel shows histogram of the events with $S/N > 2.5$ versus of period phase for 19.01.2012 (triple period).

reliability, we determine the observing window or the group as three apparent pulsar period with the sampling interval 7.5776 ms. One observation set contained 280 or 841 groups (triple periods) at frequencies 111 MHz and 42/62 MHz accordingly. The direct integration of all groups showed week signal with signal-to-noise (S/N) ratio about 5 in some observations. But if we used the method of visible pulses selection (Malofeev et al. 2012) for reduction of data in these observations, the value of S/N ratio can reach more than 10 in these days (Fig. 1). In this case we summed all groups, where have been the pulses with $S/N > 2$ at selected phase. The mean profile of 36 such selected groups is presented at Fig. 1 (upper). The integration was carried out at phase sample 52±3, but possible see two other more week pulses at the phases near samples 21 and 83. All three pulses are separated by one pulse period (31.29 samples). Next very important thing is the presence of the signal dispersion. The dispersion tracks are seen at dynamic spectra (Fig. 1, bottom panels). We have been luck and first time new simultaneous observation at three frequencies on 20 of January give us possibility to measure more exactly the value of $DM = 2.89 \pm 0.02$. Fig. 3 shows events with $S/N > 2.5$ versus number of pulse, DM and phase of period for 19.01.2012 at 111 MHz.

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Do magnetars really exist?

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Abstract. It is shown that there are neither necessary nor sufficient properties to provide unambiguous evidence for including any object in the AXP/SGR class.

Keywords. AXPs, SGRs, magnetars, drift model

1. Expected properties of AXPs and SGRs

To answer the question in the title we must discuss some specific properties of anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). These sources are believed to be strongly magnetized neutron stars (magnetars) and can be described by some additional characteristics. These are:
1. the supercritical dipole magnetic field $B > B_{cr} = \frac{2\pi m^2 c^2}{e^2} = 4.41 \times 10^{13}$ G,
2. low losses of the rotational energy comparing with their X-ray luminosities: $L_x > \frac{4\pi I dP/dt}{\nu^3}$,
3. the bursting behaviour,
4. the black body plus power-law X-ray spectrum,
5. the erratic radio pulse behaviour,
6. they are young objects connecting with SNRs,
7. they have very long periods.

Let us consider these properties one by one.

1) Some years ago SGR0418+5729 was discovered, with $P = 9.1$ sec (Rea, Esposito & Turolla 2010). The upper limit of $dP/dt$ gives $B = 6.4 \times 10^{13}(PdP/dt)^{1/2} < 7.5 \times 10^{12}$ G. This object showed two bursts at $8 - 200$ keV during 20 minutes with energies $4 \times 10^{37}$ and $2 \times 10^{37}$ ergs (the border between AXPs and SGRs).

Recently SGR 1822-1606 has been detected (Rea, Izrael & Esposito 2008). Its surface magnetic field is equal to $2.13 \times 10^{13}$ G and less than $B_{cr}$ as for SGR0418+5729.

So, a high surface dipolar magnetic field is not necessarily required for magnetar-like activity. There are, on the other hand, 19 radio pulsars with $B_s > B_{cr}$ (Manchester et al. 2005). Hence superstrong magnetic fields are not sufficient for the appearance of an AXP/SGR.

2) The young radio pulsar PSR J1846-0258 in SNR Kes 75 ($\tau = 884$ years) with $P = 326$ msec shows X-ray bursts and strong variations of times of arrivals, i.e. it is similar to AXP/SGR. However its losses of rotation energy $dE/dt = 8.1 \times 10^{36}$ erg/sec are quite enough to provide X-ray luminosity $L_x = 4.1 \times 10^{34}$ erg/sec.

3) The bursting behaviour is the common characteristic of all anomalous pulsars. However normal radio pulsars demonstrate variations at all frequencies and at all time intervals (from nanoseconds up to several years) as well. Moreover giant radio bursts of one of subpulses are detected in a number of them (see, for example, Malofeev, Malov & Shchegoleva 1998) and even giant pulses are observed in some pulsars (Soglasnov, Popov & Bartel 2004; Popov, Kuz’mín & Ul’yanov 2006).

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Strong variability of intensity and spectral changes of components of individual pulses in AXP/XTE J1810-197 do not differ in principle from the behaviour of normal radio pulsars. Their individual pulses have not only very different intensity but their spectral indices often changes sign at low frequencies (Kuzmin, Malofeev & Shitov 1978). Thus anomalous pulsars differ from radio ones by values of parameters and by the character of their variability only.

4) Such a sum is believed typical for spectra of AXP/SGRs. However several dozens of normal radio pulsars emit thermal and non-thermal radiation also. Sometimes (as in the Crab pulsar PSR B0531+21) total spectra have very complicated form.

5) There are radio pulsars (for example, Geminga - Malofeev & Malov 1997) showing changes in intensities and forms of pulses and even in phases of pulse appearances.

6) About 20 normal radio pulsars are observed in SNRs but they do not belong to the class of AXP/SGR.

7) SGR J1627-41 has the short interval between subsequent observed pulses $P = 2.6$ sec. On the other hand some normal radio pulsars have periods of order of several seconds (Manchester et al. 2005).

2. Two additional arguments against the magnetar model

1. In the popular model of magneto-rotational explosion of supernova (Ardeljan, Bisnovatyi-Kogan & Moiseenko 2005) it is shown that magnetic fields of order of $10^{16}$ G may only exist in a new born neutron star for 1 sec.

2. The detailed calculations show that magnetic plasmas ejected from a neutron star emit neutrino radiation mainly. Electromagnetic radiation will be essential if magnetic fields in the magnetosphere $B > 10^{16}$ G (Gvozdev, Ognev & Osokina 2011).

3. Conclusions and discussion

1. There are no necessary and sufficient properties to provide unambiguous evidence for including an object in the AXP/SGR class.

2. It is not necessary to use the magnetar model for the description of observed characteristics of AXPs and SGRs. There is the alternative model: the drift model with the suggestion on drift waves in the vicinity of the light cylinder (Malov & Machabeli 2006). Neutron stars with rather short rotation periods ($P < 1$ sec) and surface magnetic fields of order of $10^{12}$ G are believed to be the central bodies of AXPs/SGRs in this model.

The specific characteristic of such objects is a small angle $\beta$ between the rotation axis of the neutron star and its magnetic moment. Indeed in those cases when radio emission of AXPs has been detected and their polarization parameters have been measured estimations give rather small values of angles $\beta$.

The radio emission of two AXPs: J1810-197 (Janssen et al. 2007) and 1E 1547.0-5408 (Camilo et al. 2008) has shown that the variations of the polarization position angles in these objects are small. The maximum derivative of the position angle $\phi$ with longitude $\Phi$ is given by

$$C = \left( \frac{d\phi}{d\Phi} \right)_{\text{max}} = \frac{\sin \beta}{\sin(\zeta - \beta)} \leq 1.$$

Here, $\zeta$ is the angle between the rotational axis of the neutron star and the line of sight toward the observer. Thus, $\zeta - \beta$ is the minimum angular distance at which the line of sight intersects the radiation cone. Setting the angular radius of this cone to be $10^\circ$, we conclude that the angle $\beta$ should be less than $10^\circ$ in J1810-197. The detection of an
interpulse in the AXP XTE J1810-197 that is offset from the main pulse by a distance other than 180° (it is approximately 240° – cf. Serylak, Stappers & Weltevrede 2008), may also directly reflect the smallness of $\beta$ for this object.

For PSR J1642-4950 we obtain $\beta = 15.6^\circ$ (Malov 2012). Hence, this object is also a nearly aligned rotator, and it is justified to apply our drift model to it.

If $\beta = 15.6^\circ$, the boundary of the magnetosphere is at a distance of the order of $4r_{LC}$, where $r_{LC}$ is the radius of the light cylinder. This makes possible the formation of appreciable pitch angles and the generation of synchrotron emission, since the ratio of the magnetic energy to plasma energy becomes less than unity. The estimates for such a case give for AXPs/SGRs values of rotation periods $P = 16 - 250$ msec and magnetic fields at the neutron star surface $B_s = 3.4 \times 10^{11} - 4.6 \times 10^{12}$ G (Malov 2010).

In the drift model the cyclotron instability can develop near the light cylinder, resulting in the generation of radio emission. It is expected that all this emission will be generated in a very narrow layer and that it will be much more intense at low frequencies (of the order of 100 MHz) than at higher frequencies (Malov 2012).

The main problem of all models is the difficulty in explaining the energetics of power gamma-ray bursts in SGRs. Apparently, it is necessary to invoke sources of energy within the neutron star. These may cause episodic ejections of plasma in the magnetosphere and releasing of its energy, for example, as a result of nuclear reactions (Malov 2012).

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Revisiting quark stars under the influence of strong magnetic fields

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Abstract. Quark matter at finite temperature and subject to strong magnetic fields is possibly present in the early stages of heavy ion collisions and in the interior of protoneutron stars. We use the mean field approximation to investigate this type of quark matter described by the Nambu–Jona-Lasinio model. The energy per baryon of magnetized quark matter becomes more bound than nuclear matter made of iron nuclei, for magnetic fields around $10^{19}$ G. When the su(3) NJL model is applied to stellar matter, the maximum mass configurations are always above 1.45 solar masses and may be as high as 1.9 solar masses for a central magnetic field of $10^{18}$ G. These numbers are within the masses of observed neutron stars but exclude the recently measured star with 1.97 solar mass.

The effect of the magnetic field on the effective quark masses and chemical potentials is only felt for quite strong magnetic fields, above $5 \times 10^{18}$ G, with larger effects for the lower densities. Spin polarizations are more sensitive to weaker magnetic fields and are larger for lower temperatures and lower densities.
The slow X-ray pulsar SXP 1062 and associated supernova remnant in the Wing of the Small Magellanic Cloud

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Abstract. SXP 1062 is an exceptional case of a young neutron star in a wind-fed high-mass X-ray binary associated with a supernova remnant. A unique combination of measured spin period, its derivative, luminosity and young age makes this source a key probe for the physics of accretion and neutron star evolution. Theoretical models proposed to explain the properties of SXP 1062 shall be tested with new data.

Keywords. stars: emission-line, Be, X-rays: binaries, pulsars: individual (SXP 1062)

1. Introduction

Neutron stars are the end products of massive-star's evolution. Stars with an initial mass in excess of $\sim 8 M_\odot$ end their life in a core-collapse supernova (SN) explosion giving birth to a degenerate compact object – a neutron star (NS) or a black hole. While the majority of massive stars are born in binary systems, only a small fraction ($\sim 10\%$) of binaries survive the SN explosion, leaving a normal star and a compact object in a binary (e.g. Iben & Tutukov 1996; Popov & Prokhorov 2006). At some point in binary evolution, the compact object will accrete matter from its companion entering the high-mass X-ray binary (HMXB) stage. The detection of pulsations from an accreting X-ray source provides strong evidence that the compact object is a NS. The majority of HMXBs consist of a NS and a Be-type star; these objects are called BeXB (see recent review by Reig 2011). The Be star wind and disk feed the NS making it an X-ray pulsar.

Pulsar spin periods in the range 1-1000 s can be explained according to the current understanding of the NS spin evolution (Reig 2011). The spin evolution can be divided into three key phases, characterized by a different energy release mechanism. These phases are known as the pulsar phase, the propeller phase, and the accretor phase. The spin period $P_{eq}$ is reached when the centrifugal and gravity forces balance. In principle, $P_{eq}$ is the maximum spin period for a given mass-accretion rate. The mass-loss rates from
OB-type stars are reasonably well known, despite the fact that the stellar winds have inhomogeneous structures (Oskinova et al. 2007, Šurlan et al. 2012)

In this canonical model, long periods in excess of 1000 s can be achieved if $B > 10^{14}$ G or $\dot{M} < 10^{12}$ g s$^{-1}$. On the other hand, a new model for wind accretion (Shakura et al. 2012) allows long spin periods and high period derivatives even for standard magnetic fields. The model predicts specific correlations between the behavior of the spin and luminosity. An alternative model to explain long-period pulsars with $P_{\text{spin}} \gg P_{\text{eq}}$ comes from Ikhsanov (2007), who postulates that prior to the accretion powered phase, a subsonic propeller phase may take place. Steady accretion under the condition $P_{\text{spin}} > P_{\text{eq}}$ can be realized when the cooling of the envelope plasma dominates the energy input.

2. SXP 1062

Until recently no source was known that allows direct study of various aspects of the theory. The situation changed dramatically with the discovery of the BeXB SXP 1062 (Hénault-Brunet et al. 2012). It was discovered during XMM-Newton and Chandra observations in April–March 2010. SXP 1062 is the first HMXB pulsar firmly associated with a supernova remnant (SNR, see Fig. 1). The SNR SXP 1062 was discovered in H$\alpha$ and [O III] filter images (Hénault-Brunet et al. 2012). The Chandra and XMM-Newton X-ray images show that the SNR is filled with X-rays.

The key observational parameters of SXP 1062 were obtained (X-ray pulse period $P = 1062$ s and X-ray spectrum) using both Chandra and XMM-Newton observations. Based on the XMM-Newton observations, Haberl et al. (2012) established the spin-down rate of SXP 1062 as $\dot{P} \approx 100$ s yr$^{-1}$. The association of the pulsar with a SNR constrains the age of the accreting NS to 10–40 kyr. Such young long period pulsars are theoretically not expected.
Figure 1 shows the location of SXP 1062 relative to the young star forming region NGC 602. Some of the most massive stars in the SMC are identified in this cluster (Evans et al. 2012). The spectral type of the optical companion was confirmed spectroscopically as B0IIIe star. Interestingly, some “normal” B-type stars have strong magnetic fields (Oskinova et al. 2011, and ref. therein), therefore an accretion of a magnetized stellar wind cannot be excluded. There are indications that SXP 1062 has long term X-ray variability. Figure 2 shows the X-ray light curve of SXP 1062 based on 11 Chandra exposures obtained in 2010.

Presently, four different explanations for the nature of SXP 1062 have been proposed. (1) Haberl et al. (2012) suggested that the NS in SXP 1062 might have been born rotating unusually slowly. If this is the case, no field decay is required. (2) Popov & Turola (2012) suggested that the NS was born as a magnetar, with an initial magnetic field $B > 10^{14}$ G. The strong magnetic braking and field dissipation led to the low $P$ and high $\dot{P}$ as observed. (3) Ikhsanov (2012) proposed that the accretion of magnetized matter can lead to the observed low $P$, while the initial and the current magnetic field strength does not exceed $6 \times 10^{13}$ G. (4) Fu & Li (2012) suggested that SXP 1062 may be an accreting magnetar, with a present-day field $B > 10^{14}$ G. New observations are needed to discriminate among these models and establish the true nature of SXP 1062.

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Seven pulsars in binary systems above the spin-up line

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Abstract. Using data from the ATNF pulsar catalogue, 186 binary pulsars are shown in the magnetic field versus spin period (B-P) diagram, and their relationship to the spin-up line is investigated. Generally speaking, pulsars in binary systems should be below the spin-up line when they get enough accretion mass from their companions. It is found that there are seven binary pulsars above the spin-up line. Based on the parameters of these seven binary systems, we describe possible reasons why they are above the spin-up line.

Keywords. Pulsar, binary, spin-up line

1. Introduction

A binary pulsar system is a pulsar with a companion, often a white dwarf, neutron star or massive star. When a neutron star is formed from the supernova, it has a high magnetic field of around $10^{11-13}$ G and slow spin period of around $0.1-10$ s. In a binary system, with the accretion mass of $0.1 \sim 0.2 M_\odot$ from the companion, a neutron star will be spun up to several milliseconds, while its magnetic field will decrease to $\sim 10^8-9$ G (Bhattacharya & van den Heuvel 1991; Manchester 2004; Stairs 2004; Manchester, Hobbs, Teoh & Hobbs 2005; Wang, Zhang & Zhao et al. 2011; Zhang, Wang & Zhao et al. 2011). During the accretion, the flow drag the field lines aside to dilute the polar field strength (Zhang & Kojima 2006). When a neutron star gets to its minimum spin period to which such a spin up proceeds in an Eddington-limited accretion, we can get the spin-up line (Bhattacharya & van den Heuvel 1991): $B_9 = P_2^{-2} R_6^{-12} m^7 \times 10^3$, where $B_9$ is the magnetic field in units of $10^9$ G, $R_6$ is the stellar radius in units of $10^6$ cm, $m$ is in unit of solar mass. After the accretion phase finishing, the radio emission of the fast rotating neutron star can be detected as millisecond pulsar whose spin period is less than 20 milliseconds (Alpar, Cheng, Ruderman & Shaham 1982; Tauris 2012).

2. Evolution of pulsars in binary systems

Up to now 186 pulsars (including 136 millisecond ones) have been found in binary systems (data from ATNF pulsar catalogue). Fig. 1 shows us their distribution in the B-P diagram. In binary systems, pulsars will evolve below the spin-up line after accreting a sufficient amount of mass from their companions. However, there are seven binary pulsars which lie above the spin-up line, as shown in Fig. 1. We arranged them into two groups according to their companion masses: the first one with the massive companions ($\dot{M} > 4.0 M_\odot$, No. 1 \sim 4) and the second one with the degenerate stars (white dwarf or neutron star, No. 5 \sim 7). The parameters of seven binary pulsars are listed in Table 1.

The common characteristics of the first group (No. 1 to 4) are their massive and non-recycled companions. They all have high eccentricities and long orbital periods. The
accretion phase has not yet started. Due to these characteristics, it can be said that they are un-recycled pulsars whose companions are still in the main sequence in binary systems. Or they are on the way of evolution, where the first born pulsars are experiencing the spin-down with no accretion.

The second group (No. 5 to 7) includes the recycled pulsars. PSR J1906+0746 (No. 5 in the Fig. 1) with mass \(1.25M_\odot\) has a neutron star companion of mass \(1.37M_\odot\). Comparing the mass of the two neutron stars, it is inferred that the heavier one is a recycled pulsar and the lighter one is a non-recycled pulsar. From the evolution history of double neutron stars, the heavier progenitor star explodes first to form a neutron star, and then the lighter one evolves until to its supernova explosion. During the evolution of the second star, the first formed neutron star will accrete matter, leading to its recycling. The short characteristic age of J1906+0746 (\(\tau=113000\) yr) indicates that it is a recently formed young pulsar after the core collapse, which is the reason why its B-P position lies above the spin-up line.

B1820-11 (No. 6 in Fig. 1) possesses a slightly massive white dwarf \(M_c=0.78M_\odot\) as its companion. From its parameters (\(\tau=3.22\) Myr, \(B=6.29\times10^{11}\) G and \(P=279.829\) ms), we suggest that it is a young recycled pulsar. If we reconsider its radius as 15 km or 20 km instead of 10 km in the spin-up line equation, then its magnetic field is about \(3.0\times10^{11}\) G and \(1.6\times10^{11}\) G, respectively. Therefore, in Fig. 1, the position of B1820-11 with the new magnetic field value will lie below the spin-up line. The evolution history of this

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>(P/) ms</th>
<th>(P_{orb}/d)</th>
<th>(e)</th>
<th>(M_c/M_\odot)</th>
<th>(\tau/) yr</th>
<th>(B/G)</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B1259-63</td>
<td>47.763</td>
<td>1236.724</td>
<td>0.8699</td>
<td>4.14</td>
<td>332000</td>
<td>3.34E11</td>
<td>NSMS</td>
</tr>
<tr>
<td>2</td>
<td>J1638-4725</td>
<td>763.933</td>
<td>1940.9</td>
<td>0.955</td>
<td>8.08</td>
<td>2.53E06</td>
<td>1.93E12</td>
<td>NSMS</td>
</tr>
<tr>
<td>3</td>
<td>J0045-7319</td>
<td>926.276</td>
<td>51.1695</td>
<td>0.8079</td>
<td>5.27</td>
<td>3.29E06</td>
<td>2.06E12</td>
<td>NSMS</td>
</tr>
<tr>
<td>4</td>
<td>J1740-3052</td>
<td>570.31</td>
<td>231.0297</td>
<td>0.5789</td>
<td>15.82</td>
<td>354000</td>
<td>3.86E12</td>
<td>NSMS</td>
</tr>
<tr>
<td>5</td>
<td>J1906+0746</td>
<td>144.072</td>
<td>0.166</td>
<td>0.0853</td>
<td>1.37</td>
<td>113000</td>
<td>1.73E12</td>
<td>DNS</td>
</tr>
<tr>
<td>6</td>
<td>B1820-11</td>
<td>279.829</td>
<td>357.762</td>
<td>0.7946</td>
<td>0.78</td>
<td>3.22E06</td>
<td>6.29E11</td>
<td>NSWD</td>
</tr>
<tr>
<td>7</td>
<td>J1141-6545</td>
<td>393.899</td>
<td>0.1977</td>
<td>0.1719</td>
<td>1.02</td>
<td>1.45E06</td>
<td>1.32E12</td>
<td>NSWD</td>
</tr>
</tbody>
</table>
pulsar can be understood in this way: the initial magnetic field of neutron star can be as high as $B \sim 10^{13}$ G, and it can evolve from the position of long spin period to that of short spin period after the neutron star accretes about $\sim 0.001M_\odot$, while one to two magnitude orders of magnetic field has been deducted.

J1141-6545 (No. 7 in Fig. 1) is a pulsar of mass $1.3M_\odot$ with an $1.02M_\odot$ optical white dwarf as its companion in binary system. With the short orbital period ($P_{\text{orbit}} = 0.1977d$) and low eccentricity ($e = 0.1719$), it can be derived that this pulsar acquired the accretion mass easily and followed up the recycled process. There is about $0.001-0.01M_\odot$ accretion mass added to this pulsar that can lead to its magnetic field deduce two magnitude orders from its initial values. Following the similar procedure of binary pulsar B1820-11 (No. 6), by setting the neutron star radius as large as $R=20$ km, the magnetic field of J1141-6545 will be about $10^{11.6}$ G, which makes this source just below the spin-up line as a new born recycled pulsar. Therefore, the evolution picture of this pulsar can be depicted like this: the progenitor of J1141-6545 may be a star with the strong magnetic field $\sim 10^{13.6}$ G, and its field decays two magnitude orders with the accreting mass of about $0.001M_\odot$.

3. Conclusion

In a binary system, with enough accreting matter from the companions, a pulsar should be below the spin-up line. With the distribution of 186 binary pulsars in B-P diagram, it is noticed that seven pulsars are above the spin-up line. Four of them have massive companions ($M > 4.0M_\odot$) and are young pulsars which are quickly spinning down. They have not started their recycling processes. The other three binary pulsars with recycled companions have not experienced the recycled processes: one system is a double neutron system. The observed pulsar is a young one with a recycled neutron star. The other two systems include degenerate stars (NS+WD), where the pulsars can be understood as newly formed recycling pulsars at the Eddington rate; and their B-P positions can be shifted to just below the spin-up line by assuming a different neutron star radius, e.g. $R = 20$ km.

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Ultra-compact X-ray binaries with high luminosity: a key for a new scenario

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Abstract. Ultra-compact X-ray binaries (UCXBs) are accreting systems with periods less than 1 hour, which qualifies them to contain a degenerate donor-companion. One would expect such systems to have the easiest theoretical explanation, compared to other kinds of X-ray binaries. Nonetheless, current theory fails to explain high mass transfer (MT) rates in three recently well observed long-period UCXBs. We find that this range of MT rates can be maintained if the donor is a remnant of an out-of-thermal-equilibrium naked core of a giant which was revealed in a very recent episode of a common envelope (CE) event.

Keywords. accretion, accretion disks, binaries: close, X-rays: binaries

1. Too high MT rates in UCXBs

Recent observations show that, at long orbital periods $> 40$ minutes, there are two groups of UCXBs widely separated in their MT rates (Heinke et al. 2012). The first group is well known and consists of transient sources with very low average MT rates, $\sim 10^{-11} M_\odot$ per yr. However, unexpectedly, the other group consists of permanent sources with average MT rates of at least two order of magnitude higher for the same orbital periods (Fig. 1). While in the first group an UCXB can belong to either the Galactic field, or be located in the direction of the bulge or in a globular cluster, in the second group all three UCXBs – 4U 1626-67, 4U 0614+09, 4U 1916-053 – belong only to the Galactic field.

The first group of long-period transient UCXBs is rather well understood in terms of MT sequence of cooling white dwarfs (WDs). The consideration that WDs are not completely degenerate at the start of the MT, and hence have some final entropy in the center, provides a range in possible MT rates for the same period. This effect is minimal for large periods, as MT was going on for already very long time and WDs are close to completion of their cooling (Deloye and Bildsten 2011, see also Fig. 1).

As for the second group of long-period persistent UCXBs, gravitational wave radiation can not provide such high MT rate even if a WD donor has finite entropy. Tidal torque provided by a circumbinary disk (CBD) can provide a stronger angular momentum loss leading to higher MT rates. However, to explain the observed MT rates (as shown on Fig. 1), the fraction of mass ending in CBD has to exceed by 10 times the one predicted by the model calibrated on cataclysmic variables (Shao and Li 2012). Other previously considered donors – an initially slightly evolved main sequence donor with a He-rich core (Nelson et al. 1986, Podsiadlowski et al. 2002), or a naked He star produced by a CE event (Yungelson 2008) – will produce MT rates too low to match observations: at long orbital periods these donors were found to be almost fully degenerate.
2. Alternative donors

A naked He core that is formed in a CE event can be larger than a WD of the same mass. It is crucial that if prior to the CE giant’s core was non-degenerate, then during and immediately after the envelope ejection it experiences thermal readjustment. This leads to a fast MT onto a companion, with MT rates reaching $10^{-2} M_{\odot} \text{yr}^{-1}$ at a peak. After a peak, MT rates are smaller but still sufficient to keep the remnant out of thermal equilibrium for a while (Ivanova 2011). How long this fast mass loss goes and how much of the core is removed during this mass loss, is not well established.

Hence, to understand high-MT UCXBs, we need to consider self-consistent He remnants. While previous studies considered evolution of initially homogeneous He stars, we formed them via simplified CE event by evolving a 5 $M_{\odot}$ star and stripping its hydrogen rich envelope. We considered cases before the start of the He core burning prior a CE, and after. The formed He remnants were evolved with different fast mass loss rates. The MT rates as of UCXBs were then obtained assuming that these out-of-thermal-equilibrium remnants are placed in a binary with a neutron star companion to start the MT, and the binary evolution is driven by gravitational wave radiation only (see Fig. 1). The remnants formed with an initially higher mass loss rate drive a higher MT rate under gravitational wave radiation because they are further out of their thermal equilibrium – for the same remnant mass, they are more inflated and colder (see Figs. 2 and 3).

We also find that the observed variations in He abundances in accretion disks of these mysterious fast-MT UCXBS do not necessarily require a WD donor. They can be explained by different durations of He core burning that took place in donor before or after
depending on the post-CE orbital separation and on the mass and entropy of a He remnant, MT can start when the donor either:

- has not yet started He burning – this can be applicable to 4U 1916-053, where the observed accretion disk is nitrogen-rich;
- is going through He burning – in this case the disk will be C/O rich, as observed for 4U 1626-67 and 4U 0614+09;
- has already completed He burning. In this case we find that the donor is less likely to be inflated enough to provide the observed MT rates.

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Global structure of the pulsar force-free magnetosphere revisited

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Abstract. A new model of the pulsar force-free magnetosphere is suggested, which includes the presence of the polar, outer and slot gaps. It is based on a new exact solution of the pulsar equation in the form of an offset monopole and the resultant split-offset monopole scheme.

Keywords. MHD, plasmas, pulsars: general, stars: neutron, stars: magnetic fields

1. Introduction

The primordial dipolar structure of the pulsar magnetic field is modified by the plasma originating in the pulsar magnetosphere. The problem of a self-consistent description of fields and currents in the pulsar magnetosphere was formulated in the form of a well-known pulsar equation (Michel 1973). The basic model is that of a stationary axisymmetric force-free dipole, where the magnetic and rotational axes are aligned, the electromagnetic forces balanced and the particle inertia is ignored.

The problem lies in guessing a current distribution which makes the self-consistent magnetic field obey the physically meaningful boundary conditions. Such a current function along with the consequent magnetic field structure was first simulated numerically in the pioneering work of Contopoulos et al. (1999). Later on these results were developed in a number of aspects (for a review see Spitkovsky, this volume). All the subsequent studies confirmed the formal validity of the original simulations of Contopoulos et al. (1999), however the physical meaning of the current function obtained is still questionable, since it implies that a part of the return current should flow through the polar gap.

We suggest to revise the commonly used set of boundary conditions in the pulsar force-free problem so as to allow for the presence of the plasma-producing gaps. Only in this case the treatment of the pulsar magnetosphere can be truly self-consistent.

2. Split-offset monopole scheme of a force-free dipole

New exact solution of the pulsar equation. An exact analytic solution of the pulsar equation is known only for a monopole located at the centre of a neutron star (Michel 1973). We have found (Petrova 2012a) that the magnetic flux function of a monopole offset by a distance \( a \) along the \( z \)-axis of the cylindrical coordinate system \((\rho, \phi, z)\),

\[
f = f_0 \left[ 1 - \frac{z - a}{\sqrt{(z - a)^2 + \rho^2}} \right], \tag{2.1}
\]

also satisfies the pulsar equation, in which case the current function \( A \) and the velocity of differential rotation \( \Omega \) are related as

\[
A = \Omega f (2 - f/f_0). \tag{2.2}
\]
Figure 1. Split-offset monopole scheme. The level lines of the magnetic flux function are presented together with the level values. Thick lines show possible current sheet locations.

As \( r \equiv \sqrt{\rho^2 + z^2} \to \infty \), Eq. (2.1) approaches the flux function of a centered monopole. At finite large distances, \( r \gg 1 \), the flux function (2.1) is an infinite series over the centered multipoles and presents a generalized multipolar solution of the pulsar equation.

Implications of the offset monopole solution. At infinity, the field of a force-free dipole is generally believed to be well represented by the classical split monopole scheme. At finite distances, however, the scheme does not allow for the consequences of essentially dipolar features. The analogy with an offset monopole enables to account for the outer gap in the pulsar magnetosphere. As the outer gap forms at the intersection of the null line with open magnetic field lines and is expected to lie entirely within the light cylinder, beyond the light cylinder the null line should coincide with a certain magnetic field line. Given that the outer gap is the place of passage of the return current, it is the critical field line that coincides with the null line, in which case both go parallel to the equator at a certain altitude above it, similarly to the case of an offset monopole.

Basics of the split-offset monopole scheme. Based on the above considerations, we suggest that beyond the light cylinder the pulsar force-free field is better represented by the split-offset monopole scheme composed of the two symmetrically offset monopoles of opposite polarity (see Fig. 1). With Eqs. (2.1)-(2.2) it is easy to show that the condition \( B^2 - E^2 \) (where \( B \) and \( E \) are the magnetic and electric field strengths, respectively) is fulfilled everywhere and for any pair \((A, \Omega)\) satisfying Eq. (2.2). Thus, the force-free approximation is valid. Furthermore, for the three horizontal lines in Fig. 1 (i.e. the two null (critical) lines and the equator) the equilibrium condition \( d(B^2 - E^2)/dz = 0 \) (e.g., Lyubarsky 1990) is valid for any relevant pair \((A, \Omega)\). Correspondingly, the four regions in Fig. 1 bounded by the three above mentioned horizontal lines may have different \((A, \Omega)\).

Current circuit configurations. In the split-offset monopole scheme, the current circuit may contain from one to three current sheets located along the null (critical) lines and the equator. In the simplest case we have \( A = \Omega = 0 \) in the equatorial region between the lines \( f = f_0 \) and \( A \neq 0 \) between the magnetic axis and these lines. Then the symmetric current sheets along the lines \( f = f_0 \) close the current circuit in each hemisphere. If in the equatorial region \( A \neq 0 \) as well, the regions on both sides of the lines \( f = f_0 \) may join without current sheets, and the return current flows in the equatorial current sheet and along the equatorial lines entering the sheet. Note that a similar structure of the equatorial region beyond the light cylinder is characteristic of the dipolar force-free magnetosphere simulated by Gruzinov (2011a,b).
3. Implications of the split-offset monopole model

Based on the split-offset monopole model, the global structure of the pulsar force-free magnetosphere seems to look as follows (see Fig. 2). The polar and outer gaps control different bundles of open field lines divided by the critical line, and the two gaps are adjusted by the slot gap located between them. Note that a similar configuration of the coexisting gaps was recently obtained in Yuki & Shibata (2012) by means of numerical simulations of the plasma particle motions in the pulsar magnetosphere. The direct current flows through the polar and slot gaps and returns to the neutron star through the outer gap. In the outer and slot gaps, the longitudinal current may change along a field line because of the trans-field currents near the light cylinder (Petrova 2012a).

Our schematic model is believed to be a proper basis for detailed analytic and numerical studies of the pulsar force-free magnetosphere. We have already started a systematic analytic description of the model (Petrova 2012b). The first results concern the region near the magnetic axis and testify to the distinction of the force-free field at the top of the polar gap from that of a pure dipole. This is attributed to the action of the transverse current flowing at the neutron star surface and closing the pulsar current circuit.

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AXPs & SGRs: Magnetar or Quarctar?

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Abstract. The concept of a “magnetar” was proposed mainly because of two factors. First, the X-ray luminosity of Anomalous X-ray Pulsars (AXPs) and Soft Gamma-Ray Repeaters (SGRs) is larger than the rotational energy loss rate \( L_x > \dot{E}_{\text{rot}} \), and second, the magnetic field strength calculated from “normal method” is super strong. It is proposed that the radiation energy of magnetars comes from its magnetic fields. Here it is argued that the magnetic field strength calculated through the normal method is incorrect at the situation \( L_x > \dot{E}_{\text{rot}} \), because the wind braking is not taken into account. Besides, the “anti-magnetar” and some other X-ray and radio observations are difficult to understand with a magnetar model.

Instead of the magnetar, we propose a “quarctar”, which is a crusted quark star in an accretion disk, to explain the observations. In this model, the persistent X-ray emission, burst luminosity, spectrum of AXPs and SGRs can be understood naturally. The radio-emitting AXPs, which are challenging the magnetar, can also be explained by the quarctar model.

1. Introduction

Anomalous X-ray Pulsars (AXPs) and Soft Gamma-Ray Repeaters (SGRs) have been generally recognized as neutron stars with super strong magnetic fields, namely magnetars. The primary properties of magnetars are:

1) The strength of magnetic field calculated from normal method is super-strong;
2) The X-ray luminosities are larger than the rotational energy loss rate, i.e. \( L_x > \dot{E}_{\text{rot}} \);
3) The radiation energy comes from the energy of the magnetic field.

Here it is argued that: 1) The magnetic field can not be calculated from normal method when \( L_x > \dot{E}_{\text{rot}} \); 2) \( L_x > \dot{E}_{\text{rot}} \) does not mean that the radiation energy is coming from the energy of the magnetic field; 3) Pulsed radio emission observed from some AXPs implies that it should be found another way to understand the observed phenomenons.

Following the arguments we present a model, quarctar, whose main properties are described below briefly.

2. Do magnetars really exist?

2.1. Is the magnetic field strength calculated from normal method correct?

When considering the following points, one finds that the method to calculate the magnetic field widely used in the literature is not suitable for AXP/SGR (Qiao et al. 2010).

1) The energy loss is carried out not only by magnetic dipole radiation but also by wind;
2) Particle acceleration and radiation depend on the electric potential in the polar cap regions;
3) If the energy carry out by the high energy particles is larger than the dipole radiation, then the value of magnetic field calculated from the classical method, i.e., the rotational energy loss equals to the dipole magnetic radiation energy loss, \( \dot{E}_{\text{rot}} = \dot{E}_{\text{dipole}} \), is incorrect. The wind braking should be taking into account (Tong et al. 2012). Probably, this is just the case of AXPs/SGRs.

2.2. Anti-magnetar observations: challenge to magnetars

There are observed anti-magnetar phenomena. For example, in PSR J1852+0040, \( P = 105 \text{ ms}, \dot{P} = (8.68 \pm 0.09) \times 10^{-18} \text{ s s}^{-1} \), the surface magnetic field is \( B_s = 3.1 \times 10^{10} \text{ G} \), which is the weakest magnetic field ever measured for a young neutron star. Its X-ray luminosity is \( L_X = 5.3 \times 10^{33} (d/7.1 \text{ kpc})^2 \text{ erg s}^{-1} \), while the rotational energy loss is \( \dot{E}_{\text{rot}} = 3.0 \times 10^{32} \text{ erg s}^{-1} \); thus \( L_X/\dot{E}_{\text{rot}} \simeq 17.7 \) (Halpern & Gotthelf 2010). This means that: \( L_x > \dot{E}_{\text{rot}} \), which does not mean super-strong magnetic field at all! Beside that, some observations show that weak field “anti-magnetar” neutron star is still not ruled out for SN1987A (Manchester 2007; Gotthelf & Halpern 2008).

2.3. Radio observations: the difference between radio pulsars and magnetars does not originate from the difference of magnetic fields

Previous observations mainly show that: (1) no radio emission from magnetars are observed; (2) the magnetic fields of magnetars are stronger than those of normal radio pulsars. Then it is generally believed that these differences are caused by the difference of the magnetic fields.

Recent observations show that all these two differences are confusing: some radio pulsars have stronger magnetic field than that of some AXPs (such as Hobbs et al. 2004; Kaspi & McLaughlin 2005); radio emission from some AXPs are observed clearly after X-ray flare (Halpern et al. 2005; Camilo et al. 2006; Lazaridis et al. 2008). These mean that the differences between radio pulsars and magnetars do not originate from the difference of magnetic fields strength.

3. AXPs & SGRs are quarctars?

Instead of the magnetars, we suggested a quarctar model: a quark star with a crust in an accretion disk to account for the X-ray and radio emission properties.

3.1. Quark star with crust: X-ray emission

It is assumed that crust of quark stars would be formed after a supernova explosion (e.g. Alcock et al. 1986). This kind of quark stars can not be observed as radio pulsars, but bare quark stars can be observed as radio pulsars (Xu et al. 2001). Therefore quark star with crust may be observed in X-ray bands. The pulse profiles in X-ray light curves should be wider and consistent with observations.

3.2. Quark star with two polar holes: radio emission

In the super flare, owning to the out-flow of high energy particles from the polar cap regions, two holes will form in the crust after some time. In this case, the polar cap regions become “bare”, so that it can generate radio emission from the bared regions. Since the quark star lies in an accretion disk, later, the polar holes will be filled by the accreted matter, hence it becomes radio quite. This scenario is consistent with observations.
Figure 1. A quark star with a crust in an accretion disk, namely quarctar. Around the quark star there is a crust, in normal case, we can just observe radiation in X-ray bands; in the super flare, high energy particles flowing out from the pole cap regions, so there are two polar cap holes formed in the crust, in this case one can observe radio emission from polar cap regions.

### 3.3. Energy source of the radiations

*Phase transition energy* comes from the phase transition of normal matter to strange matter that takes place near the polar cap regions of the strange stars with a crust. For a magnetized star, the accreting material falls to the surface through the magnetic tube along the open field lines. The ions can be formed at the polar cap regions. The ions can be supported by the electromagnetic force. However, this balance can be destroyed easily, so that the normal matter can be transferred to the quark matter. This is a way to support the energy loss from the polar cap regions.

Xu et al. (2006) suggested that the energy of superflares of SGR can be supported by giant quakes in solid quark stars, which is a rich energy source for SGRs.

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Searches for continuous gravitational waves with the LIGO and Virgo detector

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Abstract. The LIGO Scientific Collaboration and Virgo Collaboration have carried out joint searches in LIGO and Virgo data for periodic continuous gravitational waves. These analyses range from targeted searches for gravitational-wave signals from known pulsars, for which precise ephemerides from radio or X-ray observations are used in matched filters, to all-sky searches for unknown neutron stars, including stars in binary systems. Between these extremes lie directed searches for known stars of unknown spin frequency or for new unknown sources at specific locations, such as near the galactic center or in globular clusters. Recent and ongoing searches of each type will be summarized, along with prospects for future searches using data from the Advanced LIGO and Virgo detectors.

Keywords. Gravitational waves, Relativity, Instrumentation: interferometers, Stars: neutron, Pulsars
116 known pulsars in the LIGO band. Highlights from the search included a lowest-strain upper limit of $2.3 \times 10^{-26}$ (J1603-7202) and a lowest stellar ellipticity limit of $7 \times 10^{-8}$ (J2124-3358). In addition, a limit of 2% was placed on the fraction of rotational energy loss of the Crab pulsar that can be attributed to gravitational radiation. A more recent search (see Abadie et al. 2011) in Virgo VSR2 data for the Vela pulsar at an expected gravitational wave frequency of about 22 Hz (for which Virgo sensitivity is substantially better than LIGO’s) yielded an upper limit of about 35% on Vela’s fractional energy loss due to gravitational waves.

Because of computational costs of searching long observations times without a priori knowledge of gravitational wave frequency evolution, one must make tradeoffs in directed searches for particular objects or points in the sky. A published broadband search (see Abbott et al. 2010) for the X-ray-emitting compact central object in the Cassiopeia supernova remnant provides one example, based on analysis of a subset of LIGO S5 data (time span of $\sim 12$ days), for which the lowest strain upper limit was $7 \times 10^{-25}$ at $\sim 150$ Hz. Because Cas A is only about 300 years old, this search incorporated a search over spin frequency and over its 1st and 2nd time derivatives. The resulting large parameter space volume for even a single point on the sky led to degraded strain sensitivity, compared to that achieved in the targeted searches described above.

All-sky searches for unknown neutron stars must cope with a still larger parameter space volume (as quantified by number of distinct templates searched for a fixed maximum SNR mismatch). Figure 1 shows all-sky strain upper limits (Abadie et al. 2012) on spinning isolated neutron stars, based on analysis of the full S5 data set, using semicoherent sums of Doppler-demodulated Fourier transform powers from tens of thousands of observations.
half-hour intervals ("PowerFlux" algorithm). A complementary and wider-band search of S5 data, based on Fourier transforms of longer coherence time (up to 25 hours per interferometer) and using the Einstein@Home distributed-computing project, led to comparable sensitivity in a search recently submitted for publication (see Aasi et al. 2012).

Comparison of the targeted and all-sky strain upper limits shown in figure 1 confirms the expected (substantial) degradation of sensitivity for searches that must search large parameter space volumes and hence must set high SNR thresholds, to cope with otherwise increased statistical outlier counts. For this reason, the "photon astronomer" community is encouraged not only to search for new and exotic objects that could serve as potential gravitational wave candidates, e.g., nearby pulsars with high rotational energy losses, but also to determine spin rotations for known objects, such as Cas A and Scorpius X-1.

Installation of Advanced LIGO and Advanced Virgo has begun, with early operation expected circa 2015. When these detectors reach design sensitivity near the end of the decade, strain amplitude sensitivities and hence ranges within the galaxy will improve by an order of magnitude. Electromagnetic measurements could well make the difference between discovering and missing a star with a detectable gravitational wave signal.

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References

On the environments and progenitors of supernova remnants associated with highly magnetized neutron stars

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Abstract. The distinction between the high-magnetic field pulsars (HBPs, thought to be mainly rotation-powered) and magnetars (commonly believed to be powered by their super-strong magnetic fields) has been recently blurred with the discovery of magnetar-like activity from the HBP J1846–0258 in the SNR Kes 75. What determines the spin properties of a neutron star at birth and its manifestation as a magnetar-like or more classical pulsar is still not clear. Furthermore, although a few studies have suggested very massive progenitors for magnetars, there is currently no consensus on the progenitors of these objects. To address these questions, we examine their environments by studying or revisiting their securely associated SNRs. Our approach is to: 1) infer the mass of their progenitor stars through X-ray spectroscopic studies of the thermally emitting supernova ejecta, and 2) investigate the physical properties of their hosting SNRs and ambient conditions. We here highlight our detailed studies of two SNRs: G292.2–0.5, associated with the HBP J1119–6127, and Kes 73, associated with the AXP 1E 1841–045, and summarize the current view of the other (handful) HBP/magnetar-SNR associations.

Keywords. (ISM:) supernova remnants; stars: neutron; (stars:) pulsars: individual (J1119–6127, 1E 1841–045); X-rays: ISM, X-rays: individual (G292.2–0.5, Kes 73)

1. High magnetic field pulsars and magnetars: On their link, progenitors, and association with supernova remnants

The past decade has witnessed a synergy of X-ray and radio observations revealing a diversity of young isolated neutron stars with magnetic fields spanning five orders of magnitude. These include the magnetars (the anomalous X-ray pulsars, AXPs; and the soft gamma-ray repeaters, SGRs), high-magnetic field radio pulsars (HBPs), Rotating Radio Transients, and the Central Compact Objects in Supernova Remnants (SNRs), in addition to the more ‘classical’ rotation-powered pulsars like the Crab. X-ray observations of the HBP J1846–0258 in the SNR Kes 75 showed the first evidence of a magnetar-like behaviour from a Crab-like pulsar, suggesting that the class of HBPs is linked to magnetars (Kumar & Safi-Harb 2008, Gavriil et al. 2008). More recently, a magnetar was discovered with a relatively low magnetic field (Rea et al. 2010), a surprising result questioning the need for a high dipolar field \( B> B_{\text{QED}} = 4.4\times 10^{13} \text{ G} \) for magnetar-like activity. This also suggests that these objects are more common than generally believed and that there is likely an evolutionary link between the different classes of neutron stars.

While observationally there is so far no consensus on magnetar progenitors, there is accumulating evidence for them originating from very massive progenitors \( M>30M_\odot \), as inferred for SGR 1806–20 and CXOU J164710.2–455216, associated with very massive clusters (Figer et al. 2005, Muno et al. 2006), the presence of a stellar-wind blown bubble around AXP 1E 1048.1–5937 (Gaensler et al. 2005), and the Wolf-Rayet progen-
itor inferred for Kes 75 hosting HBP J1846–0258 (Morton et al. 2007). However, a lower progenitor mass of $17 M_{\odot}$ has been suggested for SGR 1900+14 (Davies et al. 2009).

To further address the link between HBPs and magnetars and their progenitors, we investigate their associated SNRs in X-rays. X-ray spectroscopy provides a powerful tool to infer the mass of the progenitor. This is achieved by fitting the X-ray spectra of young, ejecta-dominated, SNRs and comparing the fitted metal abundances to nucleosynthesis model yields. Furthermore, the parameters inferred from fitting the X-ray spectrum of the blast wave yield other intrinsic properties of the SNR (explosion energy, age, ambient density), thus shedding light on their environment and evolutionary stage.

Currently, there is only a handful of associations: two SNRs securely associated with HBPs: G292.2–0.5/J1119–6127 and Kes 75/J1846–0258, and four SNRs associated with magnetars: Kes 73/1E 1841–045, CTB 109/1E 2259+586, G327.24–0.13/1E 1547.0–5408, and G337.0–0.1/SGR 1627–41. Other proposed associations are: W41/magnetar Swift J1834.9–0846, G29.6+0.1 and CTB 37B with magnetars candidates AX J1845–0258 and CXOU J171405.7–381031, respectively, the candidate SNR G333.9+0.0/radio magnetar PSR J1622–4950, G42.8+0.6/SGR 1900+14, G353.6–0.7/magnetar candidate XMMU J173203.3–344518, and N49/SGR 0526–66 in the LMC†. We here briefly summarize our dedicated studies of G292.2–0.5 and Kes 73 (Kumar et al. 2012a, b), and conclude with a summary of the properties of their associated SNRs studied in X-rays.

2. The SNRs G292.2–0.5 and Kes 73

The SNR G292.2–0.5 is associated with the HBP J1119–6127 which has a rotation period $P \sim 408$ ms, a characteristic age $\tau \sim 1.6$ kyr (with an upper limit on its age of 1.9 kyr), and a dipole magnetic field $B \sim 4.1 \times 10^{13}$ G. The combined Chandra and XMM-Newton study shows that the plasma is best described by a two-component thermal+non-thermal model. The thermal component is fitted with a non-equilibrium ionization model with a high temperature $kT$ ranging from 1.3 keV in the western side to 2.3 keV in the east, a column density increasing from $1.0 \times 10^{22}$ cm$^{-2}$ in the west to $1.8 \times 10^{22}$ cm$^{-2}$ in the east, and a low ionization timescale ranging from $5.7 \times 10^{9}$ cm$^{-3}$ s in the SNR interior to $3.6 \times 10^{10}$ cm$^{-3}$ s in the western side. An additional hard non-thermal component for the eastern and western sides of the pulsar can be partly attributed to leakage of relativistic particles from the pulsar or its associated nebula. The spatial and spectral differences across the SNR are consistent with the presence of a dark cloud in the eastern part of the SNR absorbing the soft X-ray emission. The metal abundances inferred for the western side of the SNR are consistent with solar or sub-solar values, characterizing the emission from the supernova blast wave; while the interior regions indicate the presence of slightly enhanced abundances from Ne, Mg, Si, hinting for the first time at the presence of reverse-shocked ejecta. We infer a high progenitor mass of $\sim 30 M_{\odot}$ suggesting a type Ib/c supernova, an SNR age of $\sim 4–7$ kyr, and a low ambient density (Table 1). The discrepancy between the SNR and pulsar’s age can be attributed to a variable braking index for the pulsar which recently showed unusual timing characteristics in the radio.

For the SNR Kes 73 associated with AXP 1E 1841–045 ($P \sim 11.8$ s, $\tau \sim 4.7$ kyr, $B \sim 7 \times 10^{14}$ G), our Chandra and XMM-Newton spatially resolved spectroscopic study requires a two-component non-equilibrium ionization thermal model. The soft-component has temperatures $\sim 0.3–0.5$ keV and ionization timescales $\geq 10^{12}$ cm$^{-3}$ s with enhanced metal abundances; while the hard-component exhibits plasma temperatures $\sim 1.1–1.7$ keV and low

ionization timescales $\sim (0.5–2.8) \times 10^{11} \text{ cm}^{-3} \text{ s}$ with solar abundances. These results indicate that the soft-component arises from the reverse-shocked ejecta with most regions showing plasma that has reached ionization equilibrium, while the hard-component originates from the blast wave shocking an ambient medium with an average density of $n_0 \sim 0.5 \text{ cm}^{-3}$. We infer a progenitor mass of $\sim (25–30) M_\odot$, supporting the earlier prediction of a SN type IIL/b for the remnant, and an SNR age of $\leq 2.1 \text{ kyr}$ (Table 1).

### 3. Summary

In summary, most current studies point to highly magnetized neutron stars originating from very massive progenitors. Table 1 highlights the SNR properties of the X-ray studied associations. These results also suggest young SNRs (age $< 10 \text{ kyr}$) expanding in a relatively low-density medium for the Galactic SNRs. Further dedicated studies in X-rays and other wavelengths, as well as improved nucleosynthesis models, are needed to confirm these calculations and increase the sample of neutron star–SNR associations.

### Table 1. SNR–HBP/magnetars associations with SNR properties inferred from X-ray studies.

<table>
<thead>
<tr>
<th>SNR/PSR</th>
<th>$D$ (kpc)</th>
<th>$n_0$ (cm$^{-3}$)</th>
<th>$v$ (km s$^{-1}$)</th>
<th>Age (kyr)</th>
<th>$E_0$ (10$^{51}$ ergs)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>G292.2–0.5/J1119–6127</td>
<td>8.4</td>
<td>0.02$^{1/2}$</td>
<td>1100</td>
<td>4.2–7.1</td>
<td>0.6$f^{1/2}$</td>
<td>[1]</td>
</tr>
<tr>
<td>Kes 75/J1846–0258</td>
<td>10.6</td>
<td>0.2–1.2</td>
<td>3700</td>
<td>0.6–0.9</td>
<td>–</td>
<td>[2]</td>
</tr>
<tr>
<td>Kes 73/1E 1841–045</td>
<td>8.5</td>
<td>(0.3–0.9)$^{1/2}$</td>
<td>1000</td>
<td>1.1–2.1</td>
<td>0.2$f^{1/2}$</td>
<td>[3]</td>
</tr>
<tr>
<td>CTB 109/1E 2259+586</td>
<td>3.0</td>
<td>0.16</td>
<td>720–1140</td>
<td>7.9–9.7</td>
<td>0.7–1.8</td>
<td>[4]</td>
</tr>
<tr>
<td>CTB 37B/J1714–3810</td>
<td>10.2</td>
<td>0.2–0.4</td>
<td>–</td>
<td>0.4–3.1</td>
<td>–</td>
<td>[5]</td>
</tr>
<tr>
<td>N49/SGR 0526–66</td>
<td>50</td>
<td>1.9$f^{1/2}$</td>
<td>700</td>
<td>4.8</td>
<td>1.8$f^{1/2}$</td>
<td>[6]</td>
</tr>
</tbody>
</table>


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A high-energy catalogue of Galactic supernova remnants and pulsar wind nebulae

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Abstract. Motivated by the wealth of past, existing, and upcoming X-ray and gamma-ray missions, we have developed the first public database of high-energy observations of all known Galactic Supernova Remnants (SNRs): http://www.physics.umanitoba.ca/snr/SNRcat. The catalogue links to, and complements, other existing related catalogues, including Dave Green’s radio SNRs catalogue. We here highlight the features of the high-energy catalogue, including allowing users to filter or sort data for various purposes. The catalogue is currently targeted to Galactic SNR observations with X-ray and gamma-ray missions, and is timely with the upcoming launch of X-ray missions (including Astro-H in 2014). We are currently developing the existing database to include an up-to-date Pulsar Wind Nebulae (PWNe)-dedicated webpage, with the goal to provide a global view of PWNe and their associated neutron stars/pulsars. This extensive database will be useful to both theorists to apply their models or design numerical simulations, and to observers to plan future observations or design new instruments. We welcome input and feedback from the SNR/PWN/neutron stars community.

Keywords. ISM: supernova remnants, stars: neutron, X-rays: general, gamma rays: observations

1. Objectives

This work is primarily motivated by the study of particle acceleration: SNRs are believed to be the main production sites of high-energy cosmic rays in the Galaxy, and high-energy observations are particularly important to assess the acceleration of protons. Our catalogue (Ferrand & Safi-Harb 2012) was developed with these goals in mind:

- focus on high energies: Green’s catalogue (2009), mostly based on radio observations, is the reference for the identification and typing of Galactic SNRs. It was used as our base list. We are here focused on particle acceleration in SNRs up to TeV or PeV energies, as revealed or hinted for by their broadband X-ray and γ-ray emission.
- provide a unified view of SNRs: several observatories already offer dedicated online resources, such as source lists (notably ASCA, Chandra, Fermi, H.E.S.S.) or image galleries (notably ROSAT, Chandra, XMM-Newton). In our catalogue, all observations from the major relevant high-energy observatories are presented together for the first time. Some other websites present all observations in a specific energy domain (notably TeVCat), regardless of the putative emitting objects. Here we offer a complete and broadband (from keV to TeV) view of all Galactic SNRs.
- be up-to-date: keeping pace with the recent surge in X-ray and γ-ray observations requires at least weekly updates.
- be easy to manipulate: we store the catalogue in a relational database, which allows basic operations such as sorting or filtering.

† Canada Research Chair
‡ CITA National Fellow
2. Access

Public Access to the catalogue is granted through a dedicated website (located at www.physics.umanitoba.ca/snr/SNRcat), which provides a pre-defined, simple, almost complete view of the database.

The main page is the list of all remnants, with each row corresponding to a single object. The first columns of the table describe the SNR (identification, environment, main physical properties), while the last columns summarize the observational status of the remnants for several modern X-ray and gamma-ray instruments. Users are offered various options to sort and filter the table (see online examples).

Clicking on a row opens the full object record in a new page, with more details and references. Again a first table gives all of the properties of the remnant itself, and a second table lists all known high-energy observations of the remnant.

Users are encouraged to send corrections or comments through an online feedback form accessible from any page (www.physics.umanitoba.ca/snr/SNRcat/SNRform.php).

3. Statistics

Our catalogue provides a summary of our current knowledge of Galactic SNRs from a high-energy perspective. As of 10 October 2012, it contains:

- **309 SNR records**: the 274 objects of Green’s catalogue as of March 2009, plus 35 objects that were added in light of recent observations. 103 records mention a neutron star (NS) or NS candidate, 85 being identified as a pulsar (PSR). A pulsar wind nebula (PWN) is detected or suggested in 87 cases (which are not a subset of the former: only 62 SNRs are associated with both a PWN and a NS/PSR). Interaction of the SNR shell with a molecular cloud is reported in 64 cases, with varying levels of confidence.
- **14 records of the sighting of a supernova**, that are referred to by 14 SNR records (in a non-bijective way, and with varying levels of confidence).
- **966 records of high-energy observations** made with 20 observatories, as shown in Table 1. Note that 283 of these are actually non-detections, and that a detected emission might not be coming from the SNR, as seen in Table 2.

4. Perspectives

We believe the database will be a very useful tool for the study and modelling of individual remnants as well as to do population studies. It is work in progress, to be updated regularly following new results, in particular from instruments just starting operations (NuSTAR and H.E.S.S. II in 2012) and satellites expected to be soon launched (eROSITA, ASTROSAT, and Astro-H). In parallel, we plan to extend the catalogue in several directions in the future:

- **Objects coverage**: the database includes all SNR types, including PWNe (also referred to as plerions). Our group is currently working on making a dedicated and up-to-date catalogue of PWNe based on multi-wavelength observations, that will be integrated with the one presented here and to be released in the near future.
- **Wavelength coverage**: the database was purposely populated with high-energy observations (with particle acceleration in mind), but the long-term goal is to get a full multi-wavelength view of SNRs by tighter integration with Green’s work in the radio, and by including in-between energy domains (IR, optical, and UV).
- **Extragalactic coverage**: following Green’s catalogue, the database was deliberately limited to objects located within our Galaxy. It could be extended to extragalactic objects, mostly in the LMC and SMC.
<table>
<thead>
<tr>
<th>domain</th>
<th>instrument</th>
<th>records by instrument</th>
<th>records by domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays</td>
<td>ASCA</td>
<td>111 + 2 = 113</td>
<td>506 + 24 = 530</td>
</tr>
<tr>
<td></td>
<td>BeppoSAX</td>
<td>17 + 0 = 17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chandra</td>
<td>121 + 0 = 121</td>
<td></td>
</tr>
<tr>
<td></td>
<td>INTEGRAL</td>
<td>21 + 8 = 29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ROSAT</td>
<td>80 + 3 = 83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RXTE</td>
<td>17 + 4 = 21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suzaku</td>
<td>42 + 1 = 43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SWIFT</td>
<td>8 + 2 = 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>XMM</td>
<td>89 + 4 = 93</td>
<td></td>
</tr>
<tr>
<td>γ-rays</td>
<td>MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>COMPTEL</td>
<td>3 + 0 = 3</td>
<td>4 + 2 = 6</td>
</tr>
<tr>
<td></td>
<td>INTEGRAL</td>
<td>1 + 2 = 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AGILE</td>
<td>8 + 0 = 8</td>
<td>87 + 209 = 296</td>
</tr>
<tr>
<td></td>
<td>Fermi</td>
<td>79 + 209 = 288</td>
<td>182 + 258 = 440</td>
</tr>
<tr>
<td></td>
<td>ARGO-YBJ</td>
<td>3 + 0 = 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CANGAROO</td>
<td>5 + 7 = 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H.E.S.S.</td>
<td>4 + 4 = 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAGIC</td>
<td>7 + 12 = 19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Milagro</td>
<td>10 + 0 = 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VERITAS</td>
<td>10 + 6 = 16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Whipple</td>
<td>2 + 8 = 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ALL</td>
<td>688 + 282 = 970</td>
<td>688 + 282 = 970</td>
</tr>
</tbody>
</table>

Table 1. Number of observational records in the database, by energy domain and by instrument (numbers are the sum of successful observations and non-detections).

<table>
<thead>
<tr>
<th></th>
<th>ejecta / shock</th>
<th>compact object / wind</th>
<th>other (unrelated)</th>
<th>unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays</td>
<td>207 + 42 = 249</td>
<td>206 + 60 = 266</td>
<td>17 + 6 = 23</td>
<td>64</td>
</tr>
<tr>
<td>γ-rays</td>
<td>33 + 28 = 61</td>
<td>44 + 22 = 66</td>
<td>0 + 2 = 2</td>
<td>60</td>
</tr>
<tr>
<td>TOTAL</td>
<td>240 + 70 = 310</td>
<td>250 + 82 = 332</td>
<td>17 + 8 = 25</td>
<td>124</td>
</tr>
</tbody>
</table>

Table 2. Nature of the high-energy emission source for all observational records in the database (for the first three columns, numbers are the sum of confident and uncertain identifications). Note that the four columns are not exclusive.

Acknowledgements

We acknowledge support by the Canada Research Chairs program, the Natural Sciences and Engineering Research Council of Canada, the Canadian Institute for Theoretical Astrophysics, the Canada Foundation for Innovation, and the Canadian Space Agency.

References

The new magnetar Swift J1822.3–1606

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Abstract. On 2011 July 14, a transient X-ray source, Swift J1822.3–1606, was detected by Swift BAT via its burst activities. It was subsequently identified as a new magnetar upon the detection of a pulse period of 8.4 s. Using follow-up RXTE, Swift, and Chandra observations, we have determined a spin-down rate of $\dot{P} \sim 3 \times 10^{-13}$, implying a dipole magnetic field of $\sim 5 \times 10^{13}$ G, second lowest among known magnetars, although our timing solution is contaminated by timing noise. The post-outburst flux evolution is well modelled by surface cooling resulting from heat injection in the outer crust, although we cannot rule out other models. We measure an absorption column density similar to that of the open cluster M17 at 10′ away, arguing for a comparable distance of $\sim 1.6$ kpc. If confirmed, this could be the nearest known magnetar.

Keywords. pulsars: individual (Swift J1822.3–1606), stars: neutron, X-rays: general

1. Introduction

Over the past two decades, several new classes of neutron stars have been discovered. Perhaps the most exotic is that of the magnetars, which exhibit some highly unusual properties, often including violent outbursts and high persistent X-ray luminosities that exceed their spin-down powers.

To date, there are roughly two dozen magnetars and candidates observed†, with spin periods between 2 and 12 s, and high spin-down rates that generally suggest dipole $B$-fields of order $10^{13}$ to $10^{15}$ G. Swift has discovered several new magnetars in recent years via their outbursts (e.g. Göğüş et al. 2010; Kargaltsev et al. 2012).

One of the latest additions to the list of magnetars is Swift J1822.3–1606. This source was first detected by Swift Burst Alert Telescope (BAT) on 2011 July 14 (MJD 55756) via its bursting activities (Cummings et al. 2011). It was soon identified as a new magnetar upon the detection of a pulse period $P = 8.4377$ s (Göğüş et al. 2011). In Livingstone et al. (2011), we reported initial timing and spectroscopic results using observations from Swift, Rossi X-ray Timing Explorer (RXTE), and Chandra X-ray Observatory. We found a spin-down rate of $\dot{P} = 2.54 \times 10^{-13}$ which implies a surface dipole magnetic field $\dot{B} = 4.7 \times 10^{13}$ G, the second lowest $B$-field among magnetars. Using an additional 6 months of Swift and XMM-Newton data, Rea et al. (2012) present a timing solution and spectral analysis. They find a spin-down rate of $\dot{P} = 8.3 \times 10^{-14}$ which implies $\dot{B} = 2.7 \times 10^{13}$, slightly lower than that found in Livingstone et al. (2011). Scholz et al. (2012) present an updated timing solution and latest flux evolution using 46 observations from Swift/XRT, 32 observations from RXTE/PCA, and 5 observations from Chandra/ASIS spanning more than a year. A single archival ROSAT/PSPC observation is also analysed. In these proceedings we summarize the results of Scholz et al. (2012).

‡ The surface dipolar component of the $B$-field can be estimated by $B = 3.2 \times 10^{19}(P \dot{P})^{1/4}$ G.
2. Results

2.1. Timing Behaviour

For each Swift and Chandra observation, a pulse time-of-arrival (TOA) was extracted using a Maximum Likelihood (ML) method, which yields more accurate TOAs than the traditional cross-correlation technique (see Livingstone et al. 2009). For the RXTE observations the cross-correlation method was used, as the high number of counts make the ML method computationally expensive.

Timing solutions were then fit to the TOAs using TEMPO. We fit three solutions, one with a single frequency derivative (Solution 1), one with two derivatives (Solution 2) and one with three derivatives (Solution 3). Table 1 shows the best-fit parameters for the three solutions. The addition of higher-order derivatives significantly improves the fit with the solutions having a reduced $\chi^2/\nu$ of 5.02/72, 1.94/71, and 1.44/70, respectively. The second and third frequency derivatives serve to fit out the effects of apparent timing noise. The best-fit solution, with three significant derivatives, has a $\nu$ and $\dot{\nu}$ which imply a spin-inferred dipole magnetic field of $5.1(2) \times 10^{13}$ G, the second lowest magnetic field measured for a magnetar thus far. This $B$-field is slightly higher than the value, $2.7 \times 10^{13}$ G, measured by Rea et al. (2012) as they do not measure significant second and third frequency derivatives. For a detailed comparison of our works see Scholz et al. (2012).

2.2. Flux Evolution

We fitted the Swift and Chandra spectra with a blackbody plus power-law model using XSPEC and measured 1–10 keV fluxes. We find a best-fit $N_H = 4.53(8) \times 10^{21}$ cm$^{-2}$ and that the spectrum softens as the flux decays. The flux decay can be characterised by a double-exponential model with decay timescales of $15.5 \pm 0.5$ and $177 \pm 14$ days.

We find that the observed luminosity decay is also well reproduced by models of thermal relaxation of the neutron-star crust following the outburst. We follow the evolution of the crust temperature profile by integrating the thermal diffusion equation. The calculation and microphysics follow Brown & Cumming (2009) who studied transiently accreting neutron stars, but with the effects of strong magnetic fields on the thermal conductivity included (Potekhin et al. 1999). We assume $B = 6 \times 10^{13}$ G, similar to the value inferred from the spin down and a $1.6 M_\odot$, $R = 11.2$ km neutron star.

We obtain good agreement with the observed light curve for times < 100 days with an injection of $\sim 3 \times 10^{42}$ ergs of energy at low density $\sim 10^{10}$ g cm$^{-3}$ in the outer crust at the start of the outburst (Figure 1). This conclusion comes from matching the observed timescale of the decay, and is not very sensitive to the choice of neutron-star parameters. We find that it is difficult to match the observed light curve at times $\gtrsim 200$ days, but the late time behaviour is sensitive to a number of physics inputs associated with the inner crust. We will investigate the late-time behaviour in more detail in future work.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Solution 1</th>
<th>Solution 2</th>
<th>Solution 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ (s$^{-1}$)</td>
<td>0.1185154253(3)</td>
<td>0.1185154306(5)</td>
<td>0.1185154343(8)</td>
</tr>
<tr>
<td>$\nu$ (s$^{-2}$)</td>
<td>$-9.6(3) \times 10^{-16}$</td>
<td>$-2.4(1) \times 10^{-15}$</td>
<td>$-4.3(3) \times 10^{-15}$</td>
</tr>
<tr>
<td>$\nu$ (s$^{-3}$)</td>
<td>-</td>
<td>$1.2(8) \times 10^{-22}$</td>
<td>$4.4(6) \times 10^{-22}$</td>
</tr>
<tr>
<td>$\dot{\nu}$ (s$^{-1}$)</td>
<td>-</td>
<td>-</td>
<td>$-2.2(4) \times 10^{-29}$</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>5.02/72</td>
<td>1.94/71</td>
<td>1.44/70</td>
</tr>
<tr>
<td>$B$ (G)</td>
<td>$2.43(3) \times 10^{13}$</td>
<td>$3.84(8) \times 10^{13}$</td>
<td>$5.1(2) \times 10^{13}$</td>
</tr>
</tbody>
</table>
2.3. Distance Estimation

As shown in the ROSAT image (Figure 2), the Galactic H\textsc{ii} region M17 is located \(\sim 20'\) southwest of Swift J1822.3–1606. It has a distance of \(1.6 \pm 0.3 \) kpc (Neilbock et al. 2001) and an absorption column density \(N_H = 4 \pm 1 \times 10^{21} \text{cm}^{-2}\) (Townsley et al. 2003) which is consistent with our best-fit value of \(4.53 \times 10^{21} \text{cm}^{-2}\). This suggests that Swift J1822.3–1606 could have a comparable distance to that of M17. If so, then Swift J1822.3–1606 would be one of the closest magnetars detected thus far.

3. Conclusions

We have presented the post-outburst radiative evolution and timing behavior of Swift J1822.3–1606. We estimate the surface dipolar component of the \(B\)-field to be \(\sim 5 \times 10^{13} \) G, although this measurement is contaminated by timing noise. By applying a crustal cooling model to the flux decay, we found that the energy deposition likely occurred in the outer crust at a density of \(\sim 10^{10} \text{g cm}^{-3}\). Based on the similarity in \(N_H\) to that of the H\textsc{ii} region M17, we argue for a source distance of \(1.6 \pm 0.3 \) kpc, one of the closest distances yet inferred for a magnetar.

References

Cummings, J. R., Burrows, D., Campana, S., et al. 2011, The Astronomer’s Telegram, 3488, 1
Göğüş, E., Kouveliotou, C., & Strohmayer, T. 2011, The Astronomer’s Telegram, 3491
X-ray properties of G308.3-1.4 and its central compact object

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Abstract. We present a short Chandra observation that confirms a previous unidentified extended X-ray source, G308.3-1.4, as a new supernova remnant (SNR) in the Milky Way. Apart from identifying its SNR nature, a bright X-ray point source has also been discovered at the geometrical center. Its X-ray spectral properties are similar to those of a particular class of neutron star known as central compact objects (CCOs). On the other hand, the optical properties of this counterpart suggest it to be a late-type star. Together with the interesting $\sim$1.4 hours X-ray periodicity found by Chandra, this system can possibly provide the first direct evidence of a compact binary survived in a supernova explosion.

Keywords. supernova remnants, X-rays

1. Introduction

Recently, we initiated an extensive identification campaign of unidentified extended ROSAT All-Sky Survey (RASS) objects (Hui et al. 2012). The brightest target in our campaign, G308.3-1.4, has already been known as a SNR candidate in the MOST SNR catalogue (Whiteoak 1992). But the limited photon statistics and the poor resolution of the RASS data do not allow any further probe of its X-ray emission properties. This has motivated us to observe G308.3-1.4 with the Chandra X-ray Observatory. The analysis of this observation is detailed in Hui et al. (2012); in these proceedings, we present a highlight of the major results.

2. Confirmation of G308.3-1.4 as a new SNR

The X-ray image of the field around G308.3-1.4 obtained by Chandra is displayed in Figure 1. An incomplete shell-like X-ray structure is found to be well-correlated with the radio shell structure. The radio contours are obtained from the 843 MHz Sydney University Molonglo Sky Survey (Bock et al. 1999). Together with the X-ray spectral analysis of the extended emission which suggests it is a shock-heated plasma with a temperature in a range of $kT \sim 0.6 – 1$ keV (see Table 2 and Fig. 8 in Hui et al. 2012), our observation unambiguously confirms G308.3-1.4 as a new SNR. A recent radio
investigation has come the same conclusion, suggesting G308.3-1.4 is a young to middle-aged SNR in the early adiabatic phase of evolution (De Horta et al. 2012).

3. Discovery of a new central compact object associated with G308.3-1.4

Apart from confirming the SNR nature of G308.3-1.4, our Chandra observation also enables us to search for the possible stellar remnant formed in the supernova explosion. Among 17 newly detected X-ray point sources (cf. Table 1 in Hui et al. 2012), the brightest source is the one located closest to the geometrical center of G308.3-1.4 (see Fig. 1). Its X-ray point source spectrum can be described by a double blackbody with the temperature of $kT_1 \simeq 0.1$ keV, $kT_2 \simeq 0.4$ keV and emitting areas of $R_1 \simeq 27 D_{\text{kpc}}$ km and $R_2 \simeq 35 D_{\text{kpc}}$ m respectively (see Fig. 2), where $D_{\text{kpc}}$ is the distance to G308.3-1.4 in units of 1 kpc. These are similar to those of CCOs – one of the most enigmatic manifestations of neutron stars (cf. Hui et al. 2006, 2009, 2012). The column density inferred from the CCO spectrum is consistent with that for the remnant, which suggest the possible association between the CCO and G308.3-1.4. We proceeded to search for the possible X-ray periodic signals from CCO and have found an interesting periodicity candidate of $P \sim 1.4$ hrs (Fig. 3). Together with the spectral energy distribution of its identified optical/IR counterpart, which conforms with the spectrum of a M dwarf, our results suggest a possible direct evidence for compact binary that survived in a supernova explosion (Hui et al. 2012).
Figure 2. X-ray spectrum of the emission from the position of CCO as observed with ACIS-I with the best-fit double blackbody model (upper panel) and contributions to the $\chi^2$ statistics (lower panel). The error bars represent 1σ uncertainties.

Figure 3. X-ray counts of CCO versus phase for a periodicity candidate of 1.4 hrs. Two periodic cycles are shown for clarity. The error bars represent 1σ uncertainties.

References
Observations of transients and pulsars with LOFAR international stations and the ARTEMIS backend

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Abstract. The LOw Frequency ARray – LOFAR – is a new radio interferometer designed with emphasis on flexible digital hardware instead of mechanical solutions. The array elements, so-called stations, are located in the Netherlands and in neighbouring countries. The design of LOFAR allows independent use of its international stations, which, coupled with a dedicated backend, makes them very powerful telescopes in their own right. This backend is called the Advanced Radio Transient Event Monitor and Identification System (ARTEMIS). It is a combined software/hardware solution for both targeted observations and real-time searches for millisecond radio transients which uses Graphical Processing Unit (GPU) technology to remove interstellar dispersion and detect millisecond radio bursts from astronomical sources in real-time.

Keywords. pulsars: general, telescopes: LOFAR

1. Introduction

The development of general-purpose GPUs, able to perform tasks done previously by Central Processing Units (CPUs) offers an attractive alternative for radio-astronomical applications. Because the storage and off-line processing of such a vast amount of data is difficult and costly, the new generation of radio telescopes, such as LOFAR, requires High Performance Computing (HPC) solutions to process the enormous volumes of data that are typically produced during a survey for fast radio transients (Jones et al. 2012). Real-time searches for radio transients, which use GPU technology to remove interstellar dispersion and detect radio bursts from astronomical sources in real-time are now possible. Also it is important to note that real-time processing offers the chance to react as fast as possible and to conduct follow-up observations of any event. We report here on the installation of a new backend which can be used with a single international LOFAR station. The details of the LOFAR and pulsar observations with LOFAR can be found in Stappers et al. (2011) and in Kondratiev et al. (these proceedings).
Figure 1. Two diagnostic plots made from simultaneous observations done with single inter-
national LOFAR station using HBA antennas covering 6 MHz of bandwidth and recorded with
the ARTEMIS backend (left) and the LOFAR core at the full observable bandwidth of 48 MHz
using LBA antennas (right). This example illustrates that international LOFAR stations could
be used together with the LOFAR core for simultaneous observations.

2. ARTEMIS – backend for international LOFAR stations

ARTEMIS is a combined hardware/software backend, which attaches in a non-disruptive
way to the LOFAR station hardware. The hardware consists of 4 12-core servers host-
ing high-end NVIDIA GPU cards. These servers are all fed data through a broadband
(10 Gigabit Ethernet) switch, which is also responsible for sending the data back to
the Netherlands during the normal International LOFAR Telescope (ILT) operations.
The data being processed adds up to a stream of 3.2 Gbits/s, which consists of a sky
bandwidth of approximately 48 MHz, sampled at 5 µs intervals, in two polarisations.
Real-time processing generally ensures that the 400 MB of data per second are reduced
to manageable rates both for storage and further processing.

The ARTEMIS servers can perform in real-time all the operations necessary to discover
short duration radio pulses from pulsars and fast transients, thanks to a modular software
structure operating in a C++ scalable framework developed at the University of Oxford.
ARTEMIS includes processing modules for receiving the data, further channelisation in
finer frequency channels using a polyphase filter, generation of Stokes parameters, ex-
cision of terrestrial radio frequency interference, temporal integration, real-time brute
force de-dispersion using typically at least 2000 trial dispersion measure (DM) values
and detection of interesting signals, in high-throughput CPU and GPU code. The GPU
processing allows a full search in DM space up to a maximum DM as defined by argu-
ments related to interstellar scattering and with the necessary DM resolution (Armour
et al. 2012). Simulations show that typically a few thousand trial DMs are sufficient to
optimally sample the DM range within all LOFAR bands.

At present, GPU based ARTEMIS hardware exists at the international stations in the
UK and France (Chilbolton and Nançay). This allows these stations to take advantage of
the most powerful technique of rejecting signals of terrestrial origin: the direct comparison
doing simultaneous listening between distant sites, also referred to as anti-coincidence testing. Both these
stations can process the full available 48 MHz of beamformed data. In addition two test
installations exist at the stations in Jülich (Germany) and Onsala (Sweden), each able
to process 12 MHz of sky bandwidth.
3. GPU advances in ARTEMIS

The first GPU project with ARTEMIS has been to focus on the de-dispersion step in the transients pipeline. This is clearly the most computationally intensive part of the pipeline and a preliminary study of different technologies has proved GPUs to be the most suitable accelerators for de-dispersion.

Figure 2 illustrates the speed-up that has been achieved using GPUs and compares the fastest GPU algorithm on NVIDIA Fermi and Kepler based hardware. This work has led to development of the fastest de-dispersion code in the world, with rough estimation that the new Kepler algorithm is over 2.5 times faster than previous Fermi code. The Shared Memory algorithm in Figure 2 has a maximum DM limit of 100. With this limit a throughput of approximately 12 Gb/s of LOFAR data can be achieved by the de-dispersion algorithm on a Kepler K10 GPU. This DM limit can be relaxed by using a different algorithm, called the L1 algorithm, which can still comfortably process a 3.2 Gb/s single station LOFAR data stream up to a DM of 500 on a K10. It is estimated that with 10 NVIDIA K10 GPUs the L1 algorithm could process a 127-beam Tied-Array with 2000 channels in each pencil beam to a maximum DM of 250.

References

Evidence for nonlinear and chaotic behaviour in pulsar spin-down rates

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Abstract. We present evidence for chaotic dynamics in pulsar spin-down rates originally measured by Lyne et al. (2010). Using techniques that allow us to re-sample the original measurements without losing structural information, we have searched for evidence for a strange attractor in the time series of frequency derivative for each pulsar. Our measurements of correlation dimension and Lyapunov exponent show, particularly in the case of PSR B1828-11, that the underlying behavior appears to be driven by a strange attractor with approximately three governing nonlinear equations.
New constraints on Preferred Frame Effects from binary pulsars

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Abstract. Preferred frame effects (PFEs) are predicted by a number of alternative gravity theories which include vector or additional tensor fields, besides the canonical metric tensor. In the framework of parametrized post-Newtonian (PPN) formalism, we investigate PFEs in the orbital dynamics of binary pulsars, characterized by the two strong-field PPN parameters, \(\hat{\alpha}_1\) and \(\hat{\alpha}_2\). In the limit of a small orbital eccentricity, \(\hat{\alpha}_1\) and \(\hat{\alpha}_2\) contributions decouple. By utilizing recent radio timing results and optical observations of PSRs J1012+5307 and J1738+0333, we obtained the best limits of \(\hat{\alpha}_1\) and \(\hat{\alpha}_2\) in the strong-field regime. The constraint on \(\hat{\alpha}_1\) also surpasses its counterpart in the weak-field regime.

Keywords. Gravitation, pulsars: general, pulsars: individual (J1012+5307, J1738+0333)

1. Introduction

Pulsars are extremely stable electromagnetic emitters, and along with their extreme physical properties and surrounding environments, they provide useful astrophysical laboratories to study fundamental physics (Lorimer & Kramer 2005). Radio timing of binary pulsars maps out the binary orbital dynamics through recording the time-of-arrivals of the pulsar signals at the telescope. For millisecond pulsars this can be done with high precision, providing a powerful tool to probe gravity (see e.g., Stairs 2003 and Kramer et al. 2006). In this work, we summarize new results on testing the local Lorentz invariance (LLI) of gravity from binary pulsars obtained by Shao & Wex (2012).

2. New Limits on Preferred Frame Effects

Non-gravitational LLI is an important ingredient of the Einstein equivalence principle (EEP) (Will 1993, 2006). But even metric gravity, which fulfills the EEP exactly, could still exhibit a violation of LLI in the gravitational sector (Will & Nordtvedt 1972, Nordtvedt & Will 1972, Damour & Esposito-Farèse 1992, Will 1993). Such a violation of LLI induces preferred frame effects (PFEs) in the orbital dynamics of a binary system that moves with respect to the preferred frame. In the parametrized post-Newtonian (PPN) formalism, PFEs of a semi-conservative gravity theory are described by two parameters, \(\hat{\alpha}_1\) and \(\hat{\alpha}_2\).

† To distinguish from their weak-field counterparts (\(\alpha_1\) and \(\alpha_2\)), here “hat” indicates possible modifications by strong-field effects.
The orbital dynamics of binary pulsars with non-vanishing $\dot{\alpha}_1$ and $\dot{\alpha}_2$ are obtained from a generic semi-conservative Lagrangian (Damour & Esposito-Farèse 1992). It is found that in the limit of small orbital eccentricity, PFEs induced by $\dot{\alpha}_1$ and $\dot{\alpha}_2$ decouple, and lead to separable effects in the timing observations. Hence they can be tested independently using observations of only one binary pulsar (Shao & Wex 2012).

- A non-zero $\dot{\alpha}_1$ induces a polarization of the eccentricity vector towards a direction in the orbital plane perpendicular to the velocity of the binary system with respect to the preferred frame, $\mathbf{w}$. The observed eccentricity vector $\mathbf{e}(t)$ is a vectorial superposition of a “relativistically rotating” eccentricity $\mathbf{e}_R(t)$ (of constant length) and a “fixed eccentricity” $\mathbf{e}_F \propto \dot{\alpha}_1$: $\mathbf{e}(t) = \mathbf{e}_R(t) + \mathbf{e}_F$ (Damour & Esposito-Farèse 1992). The effect is graphically illustrated in the left panel of Fig. 1. Previous methods use the smallness of the observed eccentricity, combined with probabilistic considerations concerning the unknown angle $\theta$ (the angle between $\mathbf{e}_R$ and $\mathbf{e}_F$) to constrain $\dot{\alpha}_1$ (Damour & Esposito-Farèse 1992, Wex 2000). The method developed in Shao & Wex (2012) is an extension of the method by Damour & Esposito-Farèse (1992) that does not require any probabilistic considerations concerning $\theta$. It is applicable to binary pulsars of short orbital period that have been observed for a long enough time, during which the periastron has advanced significantly. Even if the advance of periastron is not resolved in the timing observation, the constraints on the (observed) eccentricity vector can be converted into a limit on $\dot{\alpha}_1$. From the 10 years of timing and the optical observations of PSR J1738+0333 (Antoniadis et al. 2012, Freire et al. 2012) one obtains the most constraining limit,

$$\dot{\alpha}_1 = -0.4^{+3.7}_{-3.1} \times 10^{-5} \quad (95\% \text{ C.L.}),$$

which is significantly better than the current best limits from both weak field (Müller et al. 2008) and strong field (Wex 2000).

- A non-vanishing $\dot{\alpha}_2$ induces a precession of the orbital angular momentum around the direction of $\mathbf{w}$ (see the right panel of Fig. 1), which changes the observed orbital inclination. Using the long-term timing results on PSRs J1012+5307 (Lazaridis et al. 2009) and J1738+0333 (Antoniadis et al. 2012, Freire et al. 2012), Shao & Wex (2012) find an upper limit

$$|\dot{\alpha}_2| < 1.8 \times 10^{-4} \quad (95\% \text{ C.L.}),$$

† Here we choose the isotropic cosmic microwave background as the preferred frame; nevertheless, see Shao & Wex (2012) for constraints on other preferred frames.

Figure 1. Illustration of preferred frame effects in the orbital dynamics of small-eccentricity binary pulsars; see Shao & Wex (2012) for details. Left: $\dot{\alpha}_1$ tends to polarize the orbital eccentricity vector $\mathbf{e}(t)$ towards the direction perpendicular to $\mathbf{w}_\perp$ (Damour & Esposito-Farèse 1992); right: $\dot{\alpha}_2$ induces a precession of the orbital angular momentum around the direction of $\mathbf{w}$. 

(2.1)

(2.2)
which is better than the current best limit for strongly self-gravitating bodies (Wex & Kramer 2007) by more than three orders of magnitude, but still considerably weaker than the weak-field limit of $\alpha_2$ by Nordtvedt (1987).

3. Summary

We summarize results presented in Shao & Wex (2012) that proposed new tests of LLI. These yield improved constraints on PFEs from binary pulsar experiments. Specifically, limits on parameters $\hat{\alpha}_1$ and $\hat{\alpha}_2$ are obtained from long-term timing of two binary pulsars with short orbital period (see Eqs. (2.1) and (2.2)). Our extended $\hat{\alpha}_1$ test no longer requires probabilistic considerations related to unknown angles. The proposed tests have the advantage that they continuously improve with time, and will benefit greatly from the next generation of radio telescopes, like FAST (Nan et al. 2011) and SKA (Smits et al. 2009).

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Formation of Binary and Millisecond Pulsars: Puzzles and Possible Solutions

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Abstract. We present a systematic study of the evolution of intermediate- and low-mass X-ray binaries. Our calculations suggest that millisecond binary pulsars in wide orbits might have neutron stars born massive, or been formed through mass transfer driven by planet/brown dwarf-involved common envelope evolution.

Keywords. stars: millisecond pulsars, stars: evolution, MSPs: general

1. Introduction

Millisecond pulsars (MSPs) are old neutron stars (NSs) recycled during the previous intermediate/low-mass X-ray binary (I/LMXB) evolution (see Bhattacharya & van den Heuvel 1991 for a review). In the previous studies on I/LMXB evolution, a canonical NS (of mass \( \sim 1.3 - 1.4 \, M_\odot \)) was usually adopted. In this work we perform calculations of I/LMXB evolution and discuss the properties of binary and millisecond pulsars (BMSPs), taking into account different initial NS masses (Shao & Li 2012).

2. Results of I/LMXB Evolution Calculations

Figure 1 shows the fate of the I/LMXB evolution in the initial \( M_2 - P_{\text{orb}} \) diagram. The left and right panels correspond to 1.0 \( M_\odot \) and 1.8 \( M_\odot \) NS, respectively. It is seen that the allowed space for successful evolution into binary pulsars (i.e., without common envelope evolution) is larger for \( M_1 = 1.8 \, M_\odot \) than for \( M_1 = 1.0 \, M_\odot \), since the lower mass ratio in the former case can stabilize mass transfer during the IMXB evolution.

Figure 2 shows the calculated correlation between the final orbital period \( P_{\text{final}}^{\text{orb}} \) and the mass of the white dwarf (WD) (the remnant of the donor) \( M_{\text{WD}} \). Low-mass donor stars may evolve to be either He WDs or CO WDs. Intermediate-mass donors can avoid He flash due to their higher temperature, forming CO WDs. Their \( P_{\text{final}}^{\text{orb}} - M_{\text{WD}} \) distribution deviates from that of the low-mass branch obviously.

3. Comparison with BMSPs

In wide LMXBs, a specific correlation between the orbital period \( P_{\text{orb}} \) and the WD mass \( M_{\text{WD}} \) is obtained (Rappaport et al. 1995). Comparison with the observations shows that a significant population of BMSPs with He WD companion is generally consistent with this \( P_{\text{orb}} - M_{\text{WD}} \) relation. However, there seems to be a systematic deviation from the correlation for pulsars with \( P_{\text{orb}} \gtrsim 60 \, \text{d} \), which seem to have WD companions lighter than expected (Tauris 1996).

Both systematic small values of the orbital inclination and large NS mass can increase
Figure 1. The allowed parameter space in the initial orbital period vs. donor mass plane for I/LMXBs to successfully form binary pulsars with He and CO WD companions.

Figure 2. The final orbital period $P_{\text{orb}}$ as a function of the WD mass $M_{\text{WD}}$.

Figure 3. The orbital period as a function of the WD mass for MSPs with possible He WD companions.

Figure 4. The mass transferred rate (red dashed curves) and accreted masses (blue dotted curves) of the NS as a function of the final orbital period.
$M_{\text{WD}}$ for the given observed mass functions. Since there does not seem to be any observational selection effect favoring small inclination angle (Tauris 1996), we examine whether the $P_{\text{orb}} - M_{\text{WD}}$ correlation can be accounted for if the long-period BMSPs have CO WD companions. In Fig. 3 we compare the relations between $P_{\text{orb}}$ and $M_{\text{WD}}$ in the cases that the NS has an initial mass of 1.0 $M_{\odot}$ (left panel) and 1.8 $M_{\odot}$ (right panel). Also plotted are binary pulsars with measured $P_{\text{orb}}$ and $M_{\text{WD}}$ (90% probability mass range for randomly oriented orbits) for a fixed NS mass of 1.2 and 2.0 $M_{\odot}$, respectively. It is seen that some binary pulsars with $P_{\text{orb}} > 100$ d can fairly match the relation if they have massive NSs ($\sim 2 M_{\odot}$) and heavy CO WDs (although in some cases small orbital inclination angles may be required), while for those with $P_{\text{orb}} < 20$ d, statistically lighter NSs ($\sim 1.2 M_{\odot}$) seem to follow the relation better.

In Fig. 4 we show the mass transfer rate $\dot{M}_2$, and the accreted mass $\Delta M_1$ of the NS as a function of the final orbital period $P_{\text{orb}}$. It shows that in general $\dot{M}_2 \gtrsim 0.1 \dot{M}_{\text{Edd}}$, and $\Delta M_1 \lesssim 0.3 M_{\odot}$. We find that systems with initially massive NSs (1.8 $M_{\odot}$) may accrete enough mass to evolve into BMSPs with 60 d $\lesssim P_{\text{orb}} \lesssim 200$ d, while light NSs in wide binaries are more likely to be partially recycled.

For MSPs with low-mass He WD companions the above model obviously does not work. Here we suggest another possible solution. It is noted that solar-type stars are usually found to be surrounded by substellar companions (usually planets and/or brown dwarfs). One may expect that in some wide LMXBs the companion star had possessed substellar companion(s) in close orbits like “hot Jupiters”. When the star evolved on the giant branch it would become big enough to capture its planet/brown dwarf. The planet/brown dwarf spiraled into the envelope of the giant to initiate a CE phase. If there was enough orbital energy, the spiral-in process would expel the envelope of the giant, leaving a WD remnant. If the initial separation between the star and the substellar object(s) is less than tens of Solar radii, the final outcome would be an under-massive WD. A schematic view of the formation of BMSPs with planet/brown dwarf-involved CE evolution is shown in Fig. 5.

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References
Detection of Giant pulses from pulsar PSR B0950+08

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Abstract. We investigated pulse intensities of PSR B0950+08 at 112 MHz at various longitudes (phases) and detected very strong pulses exceeding the amplitude of the mean profile by more than one hundred times. The maximum peak flux density of a recorded pulse is 15240 Jy, and the energy of this pulse exceeds the mean pulse energy by a factor of 153. The analysis shows that the cumulative distribution function (CDF) of pulse intensities at the longitudes of the main pulse is described by a piece-wise power law, with a slope changing from $n=-1.25\pm0.04$ to $n=-1.84\pm0.07$ at $I>600$ Jy. The CDF for pulses at the longitudes of the precursor has a power law with $n=-1.5\pm0.1$. Detected giant pulses from this pulsar have the same signature as giant pulses of other pulsars.

Keywords. Giant pulses, PSR B0950+08, pulse intensities distribution

1. Observations and data reduction

PSR B0950 is one of the strongest pulsars at the meter wavelengths and also nearby: its flux density is $S = 2$ Jy at $f = 102$ MHz, its distance is $R = 262$ pc. The observations of PSR B0950+08 were conducted on the Large Scanning Antenna of the Pushchino Radio Astronomy Observatory at 111.846 MHz during 22 days in June ÷ July 2009. Linearly polarized emission was received. For each session we recorded 765 individual pulses with a sampling of 0.4096 ms. We used 461 channels of the digital receiver with a bandwidth per channel of 5 kHz. We recorded pulses in a window of 200 ms covering the range of the pulse and out-of-pulse in all channels. For each session, we calculated the peak amplitude of the mean profile $A$, signal-to-noise ratio $S/N$ and the energy in the average pulse, obtained by summing the intensities within the mean profile at the level $I > 4\sigma_N$. The shape of the session-mean pulse and $S/N$ vary strongly from day to day, due to propagation effects in the inhomogeneous interstellar plasma which strongly modulate the intensity in both frequency and time. The characteristic temporal and frequency scales for B0950+08 at 112 MHz are $t_{dif} > 200$ s and $f_{dif} = 220$ kHz obtained by Smirnova & Shishov (2008). Therefore, diffractive scintillations do not effect the intensity variations of individual pulses within a session, only the session-to-session variation of the mean profile amplitude. The Faraday modulation period at 112 MHz corresponds to 15 MHz, which considerably exceeds the receiver bandwidth. It leads to a session-to-session change in the relative amplitude of the profile components. Accordingly, we took these effects into account in our analysis.

2. Mean profile and Giant pulses

We used the following relation to scale the pulse peak amplitudes for different days in flux-density units (Jy): $A(t)[Jy] = A(t) S \cdot k < A >$, where $S = 2$ Jy at our frequency, $k = 14.9$ is a coefficient relating to the ratio of the peak amplitude to pulse energy.
averaged over the pulsar period, and <A> is the mean value of amplitudes A(t) for the entire series of observation in relative units, <A> = 30 Jy. The mean profile obtained by summing of 17 profiles (13000 pulses) with S/N > 14 is shown in Fig. 1 by thick line. The profile has three components, with a separation between components 2 and 3, ∆S = 6.2 ms. We included here also the mean profile at 430 MHz (thin line) taken from European Pulsar Network Data Archive normalized to the same amplitude. We see the weak precursor with two unresolved components in the main pulse at 430 MHz. The frequency dependence of the profile width in this range is: W_0.5 ∝ f^{-0.35}. Our analysis of individual pulses included the determining of positions (phases) and amplitudes for subpulses with a peak amplitude which exceeded some level in units of σ_N within each pulse. We detected very strong pulses at longitudes of all three components. In Fig 2 we show giant pulses and mean profiles multiplied by 100 for two days of observation. Amplitude of the strongest pulse by 120 times exceeds the amplitude of mean profile for this day and by 508 times exceeds the amplitude of averaged for 17 days profile. Peak flux density of this pulse is 15240 Jy and energy of it is 81240 Jy*ms which exceeds the mean pulse energy by a factor of 153. We receive rare but strong pulses at the longitude of component one (precursor), their amplitude can be 490 times more than amplitude of mean profile at this longitude. We see in this figure that when emission takes place at the precursor it is absent at the longitude of the main pulse (MP) and vice-versa. In common emission becomes much weaker in MP when strong pulses exist in precursor. If we combine the profile from weak pulses (3σ_N < I < 6σ_N) at longitudes of MP we see emission in the precursor which means that weak pulses in MP do not influence it.

3. Cumulative distribution function

To exclude influence of scintillation and polarization effects on intensity variations from day to day we did the following correction of pulse intensities: I(t) = I_n(t)σ_N^n · A_0 / (σ_N^n · A_0), where σ_N^n and A_0 are sigma noise and amplitude of the mean profile for the reference day, index n corresponds to day number n. Fig. 3 shows the cumulative distribution function (CDF) of the number of pulses with I > 5σ_N taken place at longitudes of MP from 17 days of observation in log-log scale. The common number of pulses was 3385. Two lines are the result of a least-squares fit. CDF has a power law with a changing of slope from n = -1.25 ± 0.04 to n = -1.84 ± 0.07 for I > 600 Jy. We also build CDF using the same procedure but for pulses within longitudes of component 1 (precursor). We chose 5 days with pronounced intensity in the mean profiles at these longitudes. The number of pulses here was 30 times less than for MP. Data can be fitted within a power law with n = -1.5 ± 0.1. The studied properties of the precursor: strong modulation,
absence of emission in the MP in the presence of powerful GPs in the precursor range, similarity of the precursors shape with that of the mean profile obtained for strong pulses, and increase of the emission intensity at low frequencies are well explained by the mechanism proposed by Petrova (2008), involving induced scattering of the MP emission by relativistic particles of strongly magnetized plasma in the pulsar magnetosphere.

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Electric current diagnostics in the magnetosphere of neutron stars

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Abstract. Active neutron stars – SGRs, reveal the high-quality QPOs at the ‘pulsating tail’ phase. We suggest diagnostics of the trapped fireball plasma, the source of high-frequency pulsations, using coronal seismology. The trapped fireball is represented as a set of current-carrying loops - equivalent of electric circuits. Our approach gives the following magnetosphere parameters in SGRs: an electric current of $(2\,\text{–}\,8)\times10^{19}$ A, magnetic field of $(0.6\,\text{–}\,2.7)\times10^{13}$ G, and electrons density of $(1.3\,\text{–}\,6.0)\times10^{16}$ cm$^{-3}$. We show high-frequency QPOs can be self-excited for a smaller electric current than the maximum current and/or due to the parametric resonance.

Keywords. Stars: neutron, SGRs, flares, oscillations, current-carrying loops, diagnostics.

1. Introduction

Three giant flares of neutron stars (Table 1) with the energy release of $10^{44} - 5\times10^{46}$ ergs, were accompanied by high-frequency (from tens to thousands Hz) quasi-periodic X-ray pulsations (Barat et al. 1983; Strohmayer & Watts 2006). A model of the high-frequency pulsations should explain not only their periods and excitation mechanism, but also their very high frequency factor $Q \geq 10^4 \, \text{–} \, 10^5$. Currently, the most widespread models for high-frequency QPOs are based on global seismic oscillations of the magnetar. Some models of neutron stars implied the excitation of torsion oscillations of the crust with a shear during starquakes. However, Levin (2007) pointed out that the torsion modes of the crust decay very rapidly. Beloborodov & Thompson (2007) proposed that non-linear oscillations of the production of electron-positron pairs emerge during the formation of a magnetar corona consisting of a set of magnetic loops. Nevertheless, current models are unable to explain the total set of the observed properties of QPOs with frequencies of 20 to 2400 Hz and their very high Q-factor. We represent the source of the pulsations - a trapped fireball - as a set of current-carrying loops and use the analogy with the loop as an equivalent RLC-circuit (Alfven et al. 1967; Stepanov et al. 2012). The efficiency of our model is illustrated by the diagnostics of the magnetospheres of SGRs.

2. The suggested approach: an equivalent electric (RLC) circuits

The ‘trapped fireball’ can be represented as a set of current-carrying magnetic loops with various sizes whose eigen-frequencies, quality factors, and inductance are given by

$$\nu = (2\pi\sqrt{LC})^{-1}, Q = \frac{1}{R\sqrt{C}}, L = 2l\left(\ln\frac{4l}{\pi r} - \frac{7}{4}\right). \quad (1)$$

Here, $R$ and $C$ are the resistance and capacitance of the coronal loop, and the inductance $L$ specified by the length $l$ and radius $r$ of a loop. Given the energy $E = LI^2/2$ that
has been released in the flare tail, one may determine the current $I$ in the coronal loop and hence the coronal plasma density and the $\phi$-component of the magnetic field. From the observed energy release power $W = RI^2$ one can find the resistance $R$ of a loop, while from the oscillations frequency the loop's capacity $C$ may be estimated, that is, the quality factor $Q$ of the oscillations. Let us illustrate the efficiency of the proposed model.

Pulsating tail of SGR 1806-20 on 27 December, 2004. The energy released in this flare was of the order of $5 \times 10^{46}$ erg, and the energy of the “ringing tail” was of the order of $10^{44}$ ergs. Taking into account the great variety of QPO frequencies (Table 1) we will suggest that the energy stored in an “average” loop in the course of “ringing tail” is roughly $10^{43}$ erg. Supposing $l = 3 \times 10^6$ cm and $r = 3 \times 10^5$ cm, we can use Eqs. (1) to find its inductance $L \approx 5 \times 10^{-3}$ Henry. Assuming that the stored energy of an “average” loop, $E \approx 10^{43}$ ergs $= 10^{36}$ J, has been released we obtain the current $I = (2E/L)^{1/2} \approx 2 \times 10^{19}$ A, from which we estimate the $\phi$-component of the magnetic field in the loop $B_\phi \approx I/cr \approx 6 \times 10^{12}$ G. The electron-positron pairs density $n$ in the source can be obtained from the electric current $I = encS$ and the cross section of the coronal loop $S$ with the radius $r = 3 \times 10^5$ cm. For $I = 1.8 \times 10^{19}$ A, $n = 1.3 \times 10^{16}$ cm$^{-3}$, i.e., the Langmuir frequency $\nu_p \approx 1$ THz corresponds to the sub-mm wavelengths. The power of the energy release in the tail is of the order of $10^{44}$ erg/s, i.e., for an “average” loop $W = RI^2 \approx 10^{40}$ erg/s $= 10^{33}$ W. The resistance of a loop is $R = W/I^2 \approx 3 \times 10^{-6}$ Ohm. One of the possible reasons for resistance may be the plasma wave instability driven by beams of high-energy electrons, accelerated in electric fields of the magnetar magnetosphere. The minimum ($\nu_1 = 18$ Hz) and maximum ($\nu_3 = 2384$ Hz) frequencies in QPOs allow the capacity of loops to be estimated from Eqs. (1): $C_1 \approx 1.3 \times 10^{-2}$ F, $C_2 \approx 7 \times 10^{-7}$ F. On the other hand, the capacity of a coronal loop may be presented as $C \approx \varepsilon_A S/l$, where $\varepsilon_A = c^2/V_A^2$ is the dielectric permeability of the medium for Alfven waves (Stepanov et al. 2012). It is known than in the magnetar corona $V_A \approx c$. Therefore, $\varepsilon_A \approx 1$ and we obtain $C \approx 10^6$ cm $= 10^{-7}$ F, which is several times lower than that $C_2$ calculated from the Eq. (1). It is easy to see that with increasing $S$ as $l$ decreases (thick loop), the coincidence of the capacitance with $C_2$ and $C_1$ can be achieved. Applying the second relation from Eqs.(1), we find corresponding $Q$-factors $Q_1 \approx 2 \times 10^5$ and $Q_2 \approx 10^7$, which exceed the observed quality factors of QPOs. Note, that the coronal loop in SGRs is a system with compact parameters and Eqs.(1) can be applied. Indeed, oscillations of electric current should be in-phase in all points of a loop. On the other hands, variations of the current propagate along the loop with the Alfven velocity ($\approx c$ for SGR). Therefore, the condition of phase coincidence $\nu \approx 20 − 2500$ Hz $< c/l \approx 10^4$ Hz is satisfied.

| Table 1. Pulsating tail properties in giant flares of SGRs and magnetosphere parameters. |
|---------------------------------|-----------------|--------------------|
| SGR 0526-66 March 5, 1979      | SGR 1900+14 August 27, 1998 | SGR 1806-20 December 27, 2004 |
| Duration, s                   | ~ 200           | ~ 400              | ~ 380       |
| Energy, ergs                  | $3.6 \times 10^{44}$ | $1.2 \times 10^{44}$ | $1.3 \times 10^{44}$ |
| Main pulse period, s          | 8.1             | 5.15               | 7.56        |
| QPO frequencies, Hz           | 43              | 28,54,84,155       | 18,26,30,93,150,625,720,976,1840,2384 |
| Energy, ergs                  | $3 \times 10^{19}$ | $6 \times 10^{14}$ | $2 \times 10^{19}$ |
| Magnetic field, G             | $2.7 \times 10^{13}$ | $10^{13}$          | $6 \times 10^{12}$ |
| Electron density, cm$^{-3}$   | $6 \times 10^{16}$ | $2 \times 10^{16}$ | $1.3 \times 10^{16}$ |
3. Excitation of high-frequency QPOs of the current in coronal loops

For minor deviations of the electric current $|\ddot I| << I$, the equation for current oscillations in a loop can be presented as (Zaitsev et al. 2001):

$$L \frac{d^2 \ddot I}{dt^2} + \alpha( I^2 - I_{max}^2) \frac{d\ddot I}{dt} + \frac{\ddot I}{C} = 0 \quad (2)$$

Eq. (2) indicates that oscillations will be excited for a smaller current than the maximum current in the giant pulse of the flare, $I < I_{max}$. Parametric resonance can be another way for the excitation of magnetic loop oscillations. The electric current oscillations due to perturbations in the crust with the pumping frequency $\nu$ through a parametric interaction with a coronal loop can trigger oscillations in the loop at the frequency $\nu$, at the sub-harmonics $\nu/2$, and at the first upper frequency of the parametric resonance $3\nu/2$. The variations in coronal loop parameters can be described by the equation

$$\frac{d^2 y}{dt^2} + \nu_0^2 (1 + q \cos \nu t) y = 0 \quad (3)$$

where $\nu_0$ is the frequency of the coronal loop eigen-mode. The parameter $q$ defines the width of the zone near the parametric resonance frequency $\nu_n = n\nu/2, n = 1, 2, 3, \ldots$, namely $-q\nu_0/2 < \nu/2 - \nu_0 < q\nu_0/2$. The excitation occurs when the frequency of eigen-oscillations of the loop $\nu_0$ falls on the first instability zone, i.e., it is close to $\nu/2$. Thus for a coronal loop to be excited parametrically, it must have suitable size, density, and magnetic field. In the flare in SGR 1901+14 27, the QPO were excited due to parametric resonance: $\nu = 54$ Hz, $\nu/2 = 27$ Hz (at the observed frequency 28 Hz), $3\nu/2 = 81$ Hz (at the observed frequency 84 Hz). Therewith the frequency width of the QPO peaks is about 1-5 Hz. Note that we obtain the observed frequencies ($\nu/2 = 28$ Hz and $3\nu/2 = 84$ Hz) with a high accuracy for $\nu$ equal to 56 Hz rather than 54 Hz.

We present the source of QPOs, a trapped fireball, as a set of current-carrying loops - an equivalent electric (RLC) circuits. Nevertheless this phenomenological approach is quite effective diagnostic tool for magnetospheres very active neutron stars - Soft Gamma Repeaters. With this approach we determined the electric current in magnetospheres of SGR 0526-66, SGR 1806-20, and SGR 1900+14, electron density, and magnetic field $B < B_q = m^2 c^3 / \hbar e = 4.4 \times 10^{13}$ G. It means that the physical processes in magnetar magnetospheres at the ‘ringing tail’ phase can be studied within non-quantum electrodynamics approach.

This work was partially supported by the RFBR grants No 12-02-00616a and 11-02-00103a, the Program of Leading Scientific Schools (1625.2012.2 and 4185.2012.2), the RAS Program ‘Non-steady-state Universe’, and the Federal Goal-Oriented Program (code 2012-1.2.1-12-000-1012-010).

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Discovery of an intermittent pulsar: PSR J1839+15

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Abstract. We report the discovery of a new pulsar PSR J1839+15, having a period of 549 ms and a DM of 68 pc cm⁻³. We also present its timing solution and report the intermittent behaviour of its radio emission.

Keywords. pulsars: general, pulsars: individual (J1839+15)

1. Introduction

A blind search for pulsars along the Galactic plane covering 10% of the region between Galactic longitude 45° < l < 135° and Galactic latitude 0° < |b| < 5° was recently carried out with the Giant Metrewave Radio Telescope (GMRT). It was named ‘GMRT Galactic Plane Pulsar and Transient Survey’. The survey was carried out at 325 MHz with a bandwidth of 16 MHz, divided into 256 filterbank channels. Each field (circular region of radius ∼ 1°) was observed for 1800 s with a sampling time of 256 µs.

The advantage of observing at 325 MHz was the wide field of view (∼ 4 deg²) paired with a sensitivity of 0.6 mJy. The observations were carried out using the incoherent array (IA) mode of the GMRT. The data were written to magnetic tapes. They were extracted to network attached storage (NAS) disks of the high performance computing cluster which consists of 64 dual-core nodes. The pulsar search was carried out using SIGPROC† with extensive RFI mitigation algorithms written by one of the authors. The trial DM range used for the search was 0–1200 pc cm⁻³. The analysis was parallelised such that the DM search for a particular field was divided among the nodes. The results were written back to the NAS disks from where, they could be copied to other machines. The candidate plots thus generated, were manually scrutinised for identifying good candidates.

The follow-up timing observations continued with a new software back-end at GMRT. This provided 512 filterbank channels across a bandwidth of 33 MHz with 122.88 µs sampling. The integration time was 1800 s. The timing analysis was done using TEMPO2‡ (Hobbs et al. 2006).

2. Results

PSR J1839+15 came out as a strong candidate and was successfully confirmed in later follow-up observations. The accumulated profile from 23 detections on the pulsar is shown in Figure 1. It shows a very narrow peak. A weaker second component can be seen just before the main pulse. The region before this component may also have another, still weaker component buried in the noise. Overall, it may consist of two or

† www.sigproc.sourceforge.net
‡ www.atnf.csiro.au/research/pulsar/tempo2

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more components although polarization studies are required to confirm the same. The timing solution obtained so far is given in Table 1.

During the follow-up timing observations, the pulsar could not be detected for 278 days from 30 August 2011 to 3 June 2012. It could be detected regularly then onwards until 2 September 2012, when it was again not detected. The estimated mean flux densities for the detections are plotted in Figure 2. As can be clearly seen, the 8σ upper limits on non-detections are below the 98% confidence limit on the expected flux density. Thus, we are fairly confident that PSR J1839+15 is an intermittent pulsar with an OFF time scale of roughly 278 days. We are currently working on calculating the $\dot{P}$ in the ON and OFF states. Two different values of $\dot{P}$ would confirm this as an intermittent pulsar. There are only three more such pulsars known currently. PSR B1931+24 shows a quasi periodic ON-OFF cycle of about 30-40 days (Kramer et al. 2006), PSR J1841−0500 shows an OFF time scale of 580 days (Camilo et al. 2012) while J1832+0029 remained OFF for 650 days and 850 days in the two sampled OFF states (Lorimer et al. 2012). The reason for this behavior is not understood. Further investigations and discoveries of new members of this class may shed some light on the underlying physics.

<table>
<thead>
<tr>
<th>RA</th>
<th>18h39m06.6(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEC</td>
<td>+15°06'57′(6)″</td>
</tr>
<tr>
<td>P</td>
<td>0.54916053388(8) s</td>
</tr>
<tr>
<td>$\dot{P}$</td>
<td>2.613(6) × 10$^{-14}$ s/s</td>
</tr>
<tr>
<td>DM</td>
<td>68.1(8) pc cm$^{-3}$</td>
</tr>
<tr>
<td>Characteristic age $\tau = P/2\dot{P}$</td>
<td>0.33 Myr</td>
</tr>
<tr>
<td>Surface Magnetic Field $B_S$</td>
<td>3.83 × 10$^{12}$ G</td>
</tr>
<tr>
<td>DM Distance $= DM/n_e$</td>
<td>3 kpc$^a$</td>
</tr>
</tbody>
</table>

$^a$DM distance calculated using the model given by Cordes & Lazio (2002)

Table 1. Important parameters of PSR J1839+15. Numbers in brackets indicate 2σ errors as reported by TEMPO2 in the last digit of the given value. The error on the DM comes from local search done on the time series data.
Intermittent pulsars are a rare breed of pulsars showing very long period nulls. The cause of these nulls is a mystery. To add to the already puzzling phenomenon, it was reported (Kramer et al. 2006, Camilo et al. 2012 and Lorimer et al. 2012) that the spin-down rate is considerably higher in the ON state than in the OFF state indicating that the particle flow forming the magnetospheric currents, is different in the ON and OFF states. Another puzzling fact is that these pulsars belong to the normal pulsar population in the P–$\dot{P}$ diagram. The cause of cessation of radio emission altogether may be attributed to the reduced particle flow or it may just be a failure of coherent emission. These pulsars certainly challenge the current emission models and if well studied, may provide vital inputs for coming up with more realistic emission mechanisms.

Given the ON-OFF nature of these pulsars, they provide great motivation for extending the existing blind searches and embarking on new, sensitive blind searches even in the previously searched areas of sky. Assuming a typical duration of a big survey as 3 to 4 years and given the OFF state time scales of these pulsars, a rough estimate of the intermittent pulsar population may go up considerably, thus opening up the possibility of discovering many more of such objects.

4. Acknowledgements

We would like to thank the staff of the GMRT who have made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research.

References
Model of radio emission from spherically symmetric pulsar wind nebulae

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Abstract. We study radio emission from pulsar wind nebulae (PWNe) considering the observed spatial structure. We assume spherical symmetry of the PWN, and model the evolution of the magnetic field and the particle energy distribution. We do not consider the synchrotron cooling of particles but consider the adiabatic cooling, because we are mostly interested in the radio emission from PWNe. The model is applied to the Crab Nebula and succeeds to reproduce the observed spatially integrated spectrum in radio with a single power-law injection. In our previous work (a one-zone model), in contrast, the integrated spectrum of the Crab Nebula is reproduced by a broken power-law injection of particles. However, the spatial structure in radio is inconsistent with observations and we need a radial velocity profile which is very different from the model by Kennel & Coroniti. Further studies of the spatial structure of PWNe are important to understand the origin of the radio emission from young PWNe.

Keywords. radiation mechanisms: nonthermal, (ISM:) supernova remnants, ISM: individual (Crab Nebula), pulsar: general

1. Introduction

Pulsar wind nebulae (PWNe) are a cloud of magnetized plasma injected from a central pulsar. The magnetized plasma inside PWNe experienced many physical processes, such as the pair cascade at the pulsar magnetosphere, the bulk acceleration of the pulsar wind, and the particle acceleration at the termination shock of the pulsar wind (see reviews by e.g., Gaensler & Slane 2006; Kirk et al. 2006). We can study the physics of the pulsars and their surroundings from the emission from PWNe.

A number of studies investigating the broadband emission from PWNe were done in a one-zone evolution model (e.g., Gelfand et al. 2009; Bucciantini et al. 2011; Tanaka & Takahara 2010, 2011). They succeed in reproducing the broadband spectrum from radio to TeV $\gamma$-ray, and determine the parameters of magnetized plasma injected from central pulsars and of spin-down evolution of central pulsars. There are, however, some problems. Especially the origin of radio emitting particles is unclear in this model. We consider that the observed spatial structures of PWNe would be a important tool to understand the radio emitting particles and we need to construct the model beyond the one-zone approximation. Here we study spatially resolved radio emission from PWNe.

2. The model

The spin-down power of the central pulsar is divided into particle and magnetic energy as $L_{\text{spin}}(t) = \dot{E}_p + \dot{E}_B$. We introduce the constant parameter $\beta_0$ which is the ratio of the particle to the magnetic energy density at injection radius $r_0$ and then $L_{\text{spin}}(t) \approx \dot{E}_p(1 + \beta_0^{-1})$. 

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Figure 1. The integrated spectrum of the Crab Nebula from radio to X-rays. The observational data $<10^{14}$ Hz are fitted by the total spectrum (thick line) which is the superposition of the emission from different radius (other lines).

The radio emitting particles stream from $r_0$ to the PWN. We ignore the diffusion of the radio emitting particles and they would transport by convection. Moreover, radio emitting particles are cooled by adiabatic cooling rather than radiative cooling. The spherical symmetry and isotropic distribution function of radio emitting particles $f(r,p,t)$ satisfies

$$\frac{\partial}{\partial t} f + \vec{u} \cdot \vec{\nabla} f - \frac{p}{3} (\vec{\nabla} \cdot \vec{u}) \frac{\partial}{\partial p} f = Q_{inj},$$

where $\vec{u}(r)$ and $Q_{inj}(r,p,t)$ represent the velocity of mean flow and the injection from the central pulsar. The velocity profile is assumed to have the power-law form

$$\vec{u} = u_0 (r/r_0)^{-\alpha u} \vec{e}_r.$$  

For the injection from the central pulsar, we assume that the single power-law injection from the inner radius, i.e., $Q_{inj}(r,p,t) = q(t)p^{-\alpha p-2}\delta(r-r_0)\theta(p_{max} - p)\theta(p-p_{min})$. $q(t)$ is determined from $\xi \dot{E}_p(t) = \int_0^{4\pi} d\theta \int_0^{\infty} dp Q_{inj}(r,p,t)$, where $\xi \sim p_{min}/p_{max}$ accounts for the synchrotron cooling effect and we take $\alpha_p = 2$.

We assume the toroidal magnetic field inside the PWN, i.e., $\vec{B}(t^*, r) = B(t^*)(r/r_0)^{\alpha_B} \vec{e}_\phi$, where $t^*$ is the time the magnetic field injected at $r = r_0$. The normalization $B(t^*)$ is determined from $L_{\text{spin}}$ and $\beta_0$. The power-law index $\alpha_B = \alpha_u - 2$ is determined from the induction equation

$$\frac{D \vec{B}(t^*, r)}{Dt} = \vec{\nabla} \times (\vec{u} \times \vec{B}(t^*, r)) + (\vec{u} \cdot \vec{\nabla}) \vec{B}(t^*, r).$$

We calculate the synchrotron emission from a PWN assuming the radiation is isotropic.

3. Results

Figure 1 shows the result of the application to the Crab Nebula. We take the parameters of $\alpha_u = 1.16$, $r_0 = 3 \times 10^{-3}$ pc, $\beta_0 = 10$, $p_{max} = 500$ GeV and $p_{min} = 30$ GeV which are fitted to reproduce the spatially integrated radio spectrum of the Crab Nebula. While the
emission from infrared to X-rays reproduced by higher energy particles is not considered, the radio emitting particles account for only $\xi = 1/20$ of total particle energy injected from the Crab pulsar.

The left panel of Figure 2 shows the projected flux in MHz calculated with the same parameters as in Figure 1. On the other hand, the radio observations of the Crab Nebula in 74 MHz show almost uniform distribution of the surface brightness (Bietenholz et al. 1997). The right panel of Figure 2 shows the projected spectral index ($F_\nu \propto \nu^\alpha$) in MHz, calculated with the same parameters in Figure 1. The value $\alpha \sim 0.3$ in our calculation is different from the observed value $\alpha \sim -0.3$ (Bietenholz et al. 1997).

4. Conclusions

Radio emission from spherically symmetric PWNe is studied, and we applied the model to the Crab Nebula. In contrast to the one-zone model, the integrated spectrum of the Crab Nebula is reproduced without the injection of low energy particles of about 1 GeV. While the projected flux distribution in MHz seems consistent with the observation, the spectral index distribution is not. The advection of the particles (Eq. 2.1) and the toroidal magnetic field (Eq. 2.2) alone fail to reproduce the integrated spectrum and spatial structure simultaneously. The diffusion of the radio emitting particle may be important to reproduced the spatial structure of PWN.

Acknowledgements

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Near IR Astrometry of Magnetars

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Abstract.
We report on the progress of our five-year program for astrometric monitoring of magnetars using high-resolution NIR observations using the laser guide star adaptive optics (LGS-AO) supported NIRC2 camera on the 10-meter Keck telescope. We have measured the proper motion of two of the youngest magnetars, SGR 1806−20 and SGR 1900+14, which have counterparts with K ~21 mag, and have placed a preliminary upper limit on the motion of the young AXP 1E 1841−045. The precision of the proper motion measurement is at the milliarcsecond per year level. Our proper motion measurements now provide evidence to link SGR 1806−20 and SGR 1900+14 with neighboring young star clusters. At the distances of these magnetars, their proper motion corresponds to transverse space velocities of 350±100 km s$^{-1}$ and 130±30 km s$^{-1}$ respectively. The upper limit on the proper motion of AXP 1E 1841−045 is 160 km s$^{-1}$. With the sample of proper motions available, we conclude that the kinematics of the magnetar family are not distinct from that of pulsars.

Keywords. infrared: stars, stars: neutron, techniques: high angular resolution, astrometry, instrumentation: adaptive optics

1. Introduction
Magnetars or highly magnetized neutron stars were proposed by Thompson & Duncan (1996) as a unified model to explain the phenomena of soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). The short and intense γ-ray flares were attributed to violent reconnections of a twisted magnetic field and the anomalously high quiescent X-ray emission from AXPs was ascribed to the decay of the same strong magnetic field. Indeed, the detection of a strong SGR-like flare and rotation glitch in the AXP 1E 2259+586 by Kaspi et al. (2003) was a strong validation of the unified nature of SGRs and AXPs.

Magnetars are currently a small family with only 9 SGRs and 12 AXPs identified from X-ray data and γ-ray bursts. Of these only 2 SGRs and 4 AXPs have well identified near infrared (NIR) counterparts. Identifying NIR counterparts for magnetars and comparing their NIR emission to X-ray emission allows us to constrain their emission mechanisms. The precise localization in NIR bands also offers an excellent avenue for the measurement of proper motions of magnetars thus allowing us to identify their birth sites and estimate kinematic ages. Here we report on the progress of our campaign to for astrometric and photometric measurements of magnetars using high-resolution NIR imaging.

2. Observations & Results
The NIRC2 camera at the 10-meter Keck II telescope is designed to utilize the high resolution (∼6 milli-arcseconds) achieved by the Laser Guide Star Adaptive Optics (LGS-AO) system. We used the 10 × 10′′ “narrow” mode of the NIRC2 camera to observe the
targets over multiple epochs from 2005 till 2010. After flat-fielding and dark subtracting the images, we corrected for the instrumental distortion of NIRC2 by a polynomial transformation. In order to reduce systematic errors caused due to residual distortion, we registered each target field at the same position on the detector in each epoch. We calculated the proper motion of each star with respect to a grid of neighboring stars using the optimal weighting scheme developed in Cameron et al. (2009). In this scheme, we chose optimal weights of each star-target vector by accounting for position jitter correlations (tip-tilt anisoplanatism). The relative astrometry was corrected for the bulk motion of the field by modeling the Galactic rotation curve.

From this astrometric program, we reported the proper motions of SGR 1806−20 and SGR 1900+14 to be $350 \pm 100$ km s$^{-1}$ and $130 \pm 30$ km s$^{-1}$ (Tendulkar et al. 2012). Figure 1 shows the direction of motion of SGR 1806−20 and SGR 1900+14 with respect to their neighboring objects. The motion of both the magnetars can be traced backwards to the clusters of massive stars with which the magnetars were long associated (Fuchs et al. 1999, Vrba et al. 2000), providing a model-independent kinematic age of $\sim 650$ yr and 6 kyr respectively.

2.1. AXP 1E 1841−045

Testa et al. (2008) proposed a NIR counterpart for AXP 1E 1841−045 but the identification was not conclusive. We observed AXP 1841−045 using the LGS-AO and the NIRC2 camera on 9 epochs between 2005 and 2009. The coadded exposure time between 15 to 45 minutes at each epoch depending on the observing circumstances. The limiting magnitude for each coadded observation was $K_s \approx 21$ mag.

The left panel of Figure 2 shows a $4 \times 4''$ cutout from our $K_s$ band image around the X-ray position of AXP 1E 1841−045 (red circle, Wachter et al. 2004). We registered our NIRC2 images to the 2MASS catalog with RMS residuals of 20 milli-arcseconds. The accuracy of the 2MASS coordinates for the brightness of our registration stars ($K_s$ mag $\approx 11$) is $70 - 80$ milli-arcseconds. Testa et al. (2008) proposed star 9 as the counterpart for the AXP based on a 3-$\sigma$ photometric variability. However, our astrometry shows that it lies outside the Chandra error circle. Given the NIR flux to X-ray flux ratios for other
magnetars and the quiescent X-ray flux from AXP 1E 1841−045, it is highly probable that one of the objects in the field is the NIR counterpart of the magnetar.

Without an identified counterpart, we can only set upper limits to the proper motion of AXP 1841−045. The right panel of Figure 2 shows the proper motions of all the objects in the vicinity of the AXP. The proper motions are corrected for the motion of the Milky Way as per Tendulkar et al. (2012). The upper limit for the proper motions of any of the objects is ~4 milli-arcseconds yr$^{-1}$. At the nominal distance of Kes 73 (8.5 kpc, Tian & Leahy 2008), this corresponds to a transverse space velocity of 160 km s$^{-1}$.

3. Conclusions

Our proper motion measurements are consistent with the radio VLBI proper motion measurements of AXP 1E 1810−197 by Helfand et al. (2007) and of PSR J1550−5418 by Deller et al. (2012). With these results in hand, the space velocities of magnetars are similar to the ~200 − 300 km s$^{-1}$ velocities of pulsars (Hobbs et al. 2005).

References

The spectral energy distributions of isolated neutron stars in the resonant cyclotron scattering model

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Abstract. The X-ray dim isolated neutron stars (XDINSs) are peculiar pulsar-like objects, characterized by their very well Planck-like spectrum. In studying their spectral energy distributions, the optical/UV excess is a long standing problem. Recently, Kaplan et al. (2011) have measured the optical/UV excess for all seven sources, which is understandable in the resonant cyclotron scattering (RCS) model previously addressed. The RCS model calculations show that the RCS process can account for the observed optical/UV excess for most sources. The flat spectrum of RX J2143.0+0654 may due to contribution from bremsstrahlung emission of the electron system in addition to the RCS process.
Is magnetar a fact or fiction to us?

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Abstract.

The key point of studying AXPs/SGRs (anomalous X-ray pulsars/soft gamma-ray repeaters) is relevant to the energy budget. Historically, rotation was thought to be the only free energy of pulsar until the discovery of accretion power in X-ray binaries. AXPs/SGRs could be magnetars if they are magnetism-powered, but would alternatively be quark-star/fallback-disk systems if more and more observations would hardly be understood in the magnetar scenario.

Keywords. pulsars: general, stars: magnetars, stars: neutron

1. Introduction

Anomalous X-ray pulsars/soft gamma-ray repeaters (AXPs/SGRs) are focused because of their huge energy release and peculiar behavior, suggesting that extra energy sources besides spin and accretion powers should play an important role there. Magnetic energy would be one of the candidates, which was initially proposed. However, this viewpoint could be challenged by more and more observations. It is worth noting here that, to solve the energy budget would be a key to understand the nature of compact stars, the equation state of dense matter at supra-nuclear density.

Let’s have a brief note on the history. Rapid rotation was generally thought to be the only energy source for pulsar emission soon after the discovery of radio pulsars (Manchester & Taylor 1977) until the discovery of accretion-powered pulsars in X-ray binaries (Pringle & Rees 1972). However, AXPs/SGRs have long spin periods (thus low spindown power, their X-ray luminosities are much larger than their spindown powers) and no binary companions, which rules out spin and accretion in binary system as the power sources for the emission. It was then proposed that SGR-like bursts as well as the persistent X-ray emission could plausibly be the result of field decay of ultra-magnetic neutron stars if MHD dynamo action in the proto-stars is very effective in case that the objects spin initially at periods of $\sim 1$ ms (e.g., Duncan & Thompson 1992). Because of the starquakes in the crusts of normal neutron stars, a self-induction electric field is created. The strong electric field could initiate avalanches of pair creation in the magnetosphere and certainly accelerate particles, resulting in a so-called magnetar corona (Beloborodov & Thompson 2006), from which high-energy bursts could be observed. The power source of AXPs/SGRs is actually the magnetic energy through field-reconnection there. This magnetar model is very popular nowadays in the astrophysical community.

Unfortunately, many predictions (see following sections) in the magnetar model have never been confirmed with certainty yet by later observations, and we then have to revisit the real nature of AXP/SGRs: are they really magnetars or alternatives? We are repeatedly asking these questions (Xu 2007, Tong & Xu 2011), and try to conclude that AXP/SGRs might not be magnetars but could be quark-star/fallback-disk systems.
2. Evidence for magnetars?

The periods and period derivatives of different kinds of pulsar-like stars are shown in Fig. 1. We are summarizing possible observational evidence for magnetars below.

![P-P diagram](image)

**Figure 1**. P-P diagram. Squares are for AXPs and SGRs, the six-pointed-star is for the radio loud magnetar (from McGill online), diamonds for X-ray dim isolated neutron stars (XDINSs), stars for rotating radio transients (RRATs), and dots for normal pulsars (from the ATNF).

- Strong dipole magnetic B-fields, measured by assuming magnetic dipole braking.
- Surface B-fields inferred from cyclotron absorptions if protons are responsible.
- Magnetic confinement of the giant flare tails after sudden release of magnetic energy.
- Magnetic suppression of scattering cross-section account for luminosity $L_s \sim 10^7 L_{\text{Edd}}$.
- SGR-like bursts from the high-B PSR J1846-0258 (but, how about the low-B SGRs?).
- Energy of both persistent & burst emissions, spectral modeling (but model-dependent).

3. Challenges to the magnetar idea

- Energetic supernova remnants associated with magnetars due to initial faster spins (initial period $P_0 \sim 1$ ms) and higher B-fields ($B_0 \sim 10^{14-16}$ G).
- A proto-neutron star with small $P_0$ and high $B_0$ may result in a large kick velocity.
- No radio emissions because of high B-field (but transient emissions are detected).
- Energetic gamma-rays from outer gaps, to be detectable by Fermi-LAT.
- The unexpected discovery of a low-B SGRs, $B < 7 \times 10^{12}$ G.
- Unexpected existence of transient magnetars and high-B PSRs.
- Magnetar free precession caused by higher mountains due to higher B-field.
4. A solution?

In view of the failed predictions of the magnetar model, listed in §3, we are obliged to think about alternative scenarios of AXP/SGRs. We note that the peculiar manifestations of AXP/SGRs would relate closely their inner structures, i.e., the physics of dense matter at supranuclear density. It is well known that baryons of an evolved massive star should be significantly compressed during core-collapse supernova, but the nature of this compressed baryonic matter is still a matter of debate due to strong non-perturbative effects of the fundamental color interaction. At a few nuclear densities, neutron stars containing almost only neutrons (and other hadrons) are presumed to be born soon after supernova, while the remnant core might be composed by quark matter if the quark degrees of freedom would not be negligible there. Nonetheless, an emergence of quark-cluster state would be possible if the coupling between quarks inside compact stars is still very strong, forming a solid quark matter star (Xu 2003). An accretion-induced quake model for AXP/SGRs is then proposed (Xu et al. 2006), in which the energy release during star quakes can be estimated as high as $\Delta E = (GM^2/R)(\Delta R/R) \sim 5 \times 10^{47} (\Delta R/R)/(10^{-6})$ ergs, to be enough to power the SGR giant flares.

Strong ejection (or wind) would certainly occur during accretion-induced energy release and/or a star quake-induced burst, and the central star may undergo a period of wind braking. If AXP/SGRs are braked by wind instead of magnetic dipole radiation, then their magnetosphere structure is different from that of normal pulsars. This may explain the non-detection in Fermi observations of magnetars ( ). The extended emission around AXP 1E 1547.0-5408 may be a magnetism-powered pulsar wind nebula. Under the wind braking scenario, a braking index smaller than three is expected.

How can one finally differentiate the magnetar model and the quark-star/fallback-disk model? X-ray polarimetry may play an important role in identifying the real equation of state of dense matter at supranuclear density (Lu et al. 2012). We are expecting such an advanced facility to give a final answer to this 80-year-longstanding problem.

5. Conclusions

Both the magnetar model and the fallback disk model for AXP/SGRs are discussed. AXP/SGRs could be magnetars, but the origin and presence of strong dipole field are challenged by recent observations. Alternatively, both the bursts and persistent emissions of AXP/SGRs could be understandable in the quark-star/fallback-disk model.

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What can Fermi tell us about magnetars?

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Abstract.

We have analyzed the physical implications of Fermi observations of magnetars. Observationally, no significant detection is reported in Fermi observations of all magnetars. Then there are conflicts between outer gap model in the case of magnetars and Fermi observations. One possible explanation is that magnetars are wind braking instead of magnetic dipole braking. In the wind braking scenario, magnetars are neutron stars with strong multipole field. A strong dipole field is no longer required. A magnetism-powered pulsar wind nebula and a braking index smaller than three are the two predictions of wind braking of magnetars. Future deeper Fermi observations will help us make clear whether they are wind braking or magnetic dipole braking. It will also help us to distinguish between the magnetar model and the accretion model for AXPs and SGRs.

Keywords. pulsars: general, stars: magnetars, stars: neutron

1. Introduction

Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are peculiar pulsar-like objects. They are commonly assumed to be magnetars, magnetism-powered neutron stars. The traditional model of magnetars is that they are young neutron stars with both strong dipole field and strong multipole field (Duncan & Thompson 1992; Thompson et al. 2002). The presence of strong dipole field ensures that they can also accelerate particles to very high energy via the outer gap mechanism. Therefore, magnetar may emit high-energy gamma-rays detectable by Fermi-LAT (Cheng & Zhang 2001). These high-energy gamma-rays are rotation-powered in nature (Zhang 2003). Detection of rotation-powered activities in magnetars will help bridge the gap between magnetars and normal pulsars.

Fermi-LAT has observed the whole magnetar class. No significant detection is reported (Sasmaz Mus & Gogus 2010; Abdo et al. 2010). Thus there is a conflict between the outer gap model in the case of magnetars and Fermi observations (Tong, Song & Xu 2010, 2011). Below we will show what Fermi can tell us about magnetars.

2. Implications of Fermi observations of magnetars

We have analyzed the implications of the Fermi observation of AXP 4U 0142+61 (Sasmaz Mus & Gogus 2010; Tong, Song & Xu 2010). It is shown that there are conflicts between outer gap model in the case of AXP 4U 0142+61 and Fermi observations. The fallback disk model for AXPs and SGRs can still not be ruled out. In Fermi observations of the whole magnetar class, still no significant detection is reported. This is consistent
with our previous analysis (Abdo et al. 2010; Tong, Song & Xu 2011). The upper limit of AXP 4U 0142+62 lies already below the theoretical calculations for some parameter space (Tong, Song & Xu 2011). Future deeper Fermi observations will help us to distinguish between the magnetar model and the accretion model for AXPs and SGRs.

3. Solutions and predictions

There are two possible explanations to the non-detection in Fermi observations of magnetars. One possibility is that AXPs and SGRs are accretion-powered systems. Then it is natural that they are not high-energy gamma-ray emitters. Various observations of AXPs and SGRs can be explained naturally in the accretion scenario (Tong & Xu 2011).

The other possibility is that magnetars are wind braking. If magnetars are wind braking instead of magnetic dipole braking, then their magnetosphere structure is different from that of normal pulsars. Vacuum gaps (including outer gap) may not exist in magnetars. This may explain the non-detection in Fermi observations of magnetars (see section 4.2 in Tong et al. 2012).

In the wind braking scenario, magnetars are neutron stars with strong multipole field. A strong dipole field is no longer required. Figure 1 shows the correspond dipole field in the case of wind braking and that of magnetic dipole braking.

![Figure 1. Dipole magnetic field in the case of wind braking versus that in the case of magnetic dipole braking. A wind luminosity $L_p = 10^{35}$ erg s$^{-1}$ is assumed. The solid, dashed, and dotted lines are for $B_{\text{dip,w}} = B_{\text{dip,d}}, 0.1B_{\text{dip,d}}, 0.01B_{\text{dip,d}}$, respectively. The dot-dashed line marks the position of quantum critical magnetic field $B_{\text{QED}} = 4.4 \times 10^{13}$ G. See Figure 2 and corresponding text in Tong et al. (2012) for details.](image-url)

Recent challenging observations of magnetars may be explained naturally in the wind braking scenario: (1) The supernova energies of magnetars are of normal value; (2) The problem posed by the low-magnetic field soft gamma-ray repeater; (3) The relation between magnetars and high magnetic field pulsars; and (4) A decreasing period derivative during magnetar outbursts. A magnetism-powered (instead of rotation-powered) pulsar wind nebula will be one of the consequences of wind braking. For a magnetism-powered pulsar wind nebula, we should see a correlation between the nebula luminosity and the magnetar luminosity. The extended emission around AXP 1E 1547.0-5408 may be a magnetism-powered pulsar wind nebula. Under the wind braking scenario, a braking index smaller than three is expected. More details are presented in Tong et al. (2012).

Considering that magnetars are wind braking (both a rotation-powered and a magnetism-powered particle wind), many aspects of magnetars can be reinterpreted. For example, the “low magnetic field” magnetar SGR 0418+5729 may actually be a normal magnetar (Rea et al. 2010; Tong & Xu 2012). It is a little special since it has a special geometry, e.g. a small magnetic inclination angle. Another example is that low luminosity magnetars are more likely to have radio emissions. The reason is that low luminosity magnetars may have a similar magnetospheric structure as normal radio pulsars (Rea et al. 2012; Liu, Tong & Yuan 2012).

4. Conclusions

_Fermi_ observations of magnetars suggest magnetars may be wind braking instead of magnetic dipole braking. Future deeper _Fermi_-LAT observations will help us make clear whether magnetars are wind braking or magnetic dipole braking. It will also help us to distinguish between the magnetar model and the accretion model for AXPs and SGRs. Therefore, deeper _Fermi_-LAT observations of the magnetar class in the future are highly recommended.

Acknowledgments

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Restrictions to neutron star models based on twin-peak quasi-periodic oscillations

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Abstract. In a series of works - Török et al. (2010, 2012a) and Urbanec et al. (2010a) - we explored restrictions to neutron star properties that are implied by various models of twin-peak quasi-periodic oscillations. Here we sketch an attempt to confront the obtained mass-angular-momentum relations and limits on neutron star compactness with the parameters estimated by assuming various equations of state and the spin frequency of the atoll source 4U 1636-53.

Keywords. X-rays: binaries; stars: neutron; stars: fundamental parameters; stars: rotation

1. Introduction

Twin-peak quasi-periodic oscillations (kHz QPOs) appear in the X-ray power-density spectra of several accreting low-mass neutron star (NS) binaries. Frequencies of these QPOs follow correlations specific for a given source (see the left panel of Figure 1 for illustration). Most QPO models relate the observed frequencies to frequencies of the orbital motion inside an inner part of the accretion disc.

The consideration of various orbital QPO models for the NS sources data results in specific mass–angular-momentum (\(M–j\)) relations rather than in preferred combinations of \(M\) and \(j\) (e.g., Török et al. 2012b). For the atoll source 4U 1636-53, there is a good evidence on the NS spin frequency based on the X-ray burst measurements, Strohmayer & Markwardt (2002). Thus, one can in principle infer the angular momentum \(j\) and remove the \(M–j\) degeneracies related to the individual twin-peak QPO models.

2. Our approach

We calculate \(\chi^2\) maps resulting from the fitting of the 4U 1636-53 data for various twin-peak QPO models (RP - Stella & Vietri, 1999, Stella et al., 1999; RP1 - Bursa, 2005; RP2 - Török et al., 2010; WD - Kato, 2001; TD - Čadež et al., 2008). These maps are compared to the \(M–j\) relations calculated from several NS equations of state (EoS) assuming that the spin frequency is either 290Hz or 580Hz (from one or two hot-spot models for the X-ray bursts).

For the QPO models we (yet) assume that the influence of the NS oblateness related to the quadrupole moment \(q\) is low and it is \(q/j^2 \sim 1\). In the calculations of the NS models we use the geometry of the Hartle-Thorne spacetime (Hartle & Thorne, 1968) and utilize the set of various EoS. These are namely: SLy 4 - Rikovska-Stone et al. (2003); APR - Akmal et al. (1998); AU-WFF1, UU-WFF2 and WS-WFF3 - Wiringa et al. (1988), Stergioulas & Friedman (1995). Related details and further references are given in Urbanec et al. (2010a,b).

In the right panel of Figure 1 we illustrate the potential of such approach in the case

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Figure 1. Frequencies of the twin-peak QPOs in various NS sources. Right: The $\chi^2$ map of the RP model vs. the NS EoS. The $\chi^2$ map results from the fits of the RP model to the kHz QPO data of 4U 1636-53. The NS EoS are assumed for the rotational frequency inferred from the X-ray burst measurements. The green line indicates the best QPO $\chi^2$ for a fixed $M$. The white lines indicate the corresponding 1$\sigma$ and 2$\sigma$ confidence levels. The dashed-yellow line indicates a simplified estimate on the upper limits on $M$ and $j$ assuming that the highest observed upper QPO frequency in 4U 1636-53 is associated to the innermost stable circular orbit (ISCO).

Figure 2. Mass–angular-momentum relations and limits on the NS compactness (the same as in the right panel of Figure 1, but for several other models).

of the relativistic precession (RP) QPO model. Several other models are considered in Figure 2. The inferred NS parameters are summarized in Table 1.

3. Conclusions

The presented partial results come from the work in progress and the final assessment requires to complete a fully self-consistent consideration of the quadrupole moment influence. Nevertheless, each application of the concrete EoS clearly removes the degeneracy in mass and angular momentum determined from the QPO models. Moreover, the applied NS EoS seems to be compatible only with some of the considered QPO models and vice versa.

Acknowledgements

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Table 1. Results for geodesic QPO models. Symbols $\nu_K$, $\nu_r$ and $\nu_\theta$ denote the Keplerian and the epicyclic orbital frequencies.

<table>
<thead>
<tr>
<th>Model</th>
<th>Atoll Source 4U 1636-53</th>
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<tbody>
<tr>
<td></td>
<td>$M_{\odot}$</td>
</tr>
<tr>
<td>RP: $\nu_L = \nu_K - \nu_r$, $\nu_U = \nu_K$</td>
<td>1.9M$_\odot$</td>
</tr>
<tr>
<td>TD: $\nu_L = \nu_K$, $\nu_U = \nu_K + \nu_r$, The QPOs generated by a tidal disruption of large accreting inhomogeneities.</td>
<td>2.3M$_\odot$</td>
</tr>
<tr>
<td>RP1: $\nu_L = \nu_K - \nu_r$, $\nu_U = \nu_K$, Non-axisymmetric disc-oscillation modes whose frequencies are similar to the frequencies predicted by the RP model when $j \sim 0$.</td>
<td>1.8M$_\odot$</td>
</tr>
<tr>
<td>RP2: $\nu_L = \nu_K - \nu_r$, $\nu_U = 2\nu_K - \nu_r$, Non-axisymmetric disc-oscillation modes whose frequencies are similar to the frequencies predicted by the RP model when $j \sim 0$.</td>
<td>2.0M$_\odot$</td>
</tr>
<tr>
<td>WD: $\nu_L = 2(\nu_K - \nu_r)$, $\nu_U = 2\nu_K - \nu_r$, Another specific non-axisymmetric modes of accretion disc-oscillations.</td>
<td>–</td>
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Origin of the pulsar pulse fine structure

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Abstract. We give a new numerical model of pulsar pulse radiation through the interstellar medium (ISM) considering the propagation effects. It explains the deficit of a scattering measure at the decameter range of frequencies that leads to the possibility of detecting the pulsar pulse fine structure. The results of numerical simulation confirm that the fine structure may be detected at low frequencies and this is qualitatively agreed with the observational data.

Keywords. interstellar medium (ISM), scattering, pulsar.

1. Introduction

Despite the fact that the micro structure of pulsar radio emission was discovered more than 40 years ago (Hankins 1971) still there is no generally accepted model of an origin of this phenomenon. We consider a conception of a fine structure of pulsar radio emission that covers different time scales from nanoseconds in the centimeter wave range to milliseconds in the decameter wave range. We propose a new model of the fine structure formation that is considered as a result of the propagation of the radio pulses through the interstellar medium and subsequent processing of the received signal in the lab frame.

2. Observational Data

The model gives us the value of the scattering time constant \( \tau_{sc}(f) \) at the frequency \( f \) that describes the temporal broadening of pulses due to interstellar scattering: \( \tau_{sc}(f) = \tau_{sc,0}(f_0)(f/f_0)^{-\alpha} \), where \( \tau_{sc,0}(f_0) \) is the scattering time constant at the fixed frequency \( f_0 \) that one could take from a pulsar catalogue (usually \( f_0 = 1 \text{GHz} \)); \( \alpha \) is a power that corresponds to different spectra of spatial inhomogeneities of the electron concentration.

Figure 1. Scattering time constant at different frequencies. The normal spectrum of electron inhomogeneities (upper line); Kolmogorov spectrum of electron inhomogeneities (lower line).
Thus $\alpha = 4.0$ for the normal spectrum of the electron density fluctuations, $\alpha = 4.4$ of the Kolmogorov spectrum.

The observation in the decameter range (Ul’yanov & Zakharenko 2012) gives us the lower value of the scattering measure for anomalous-intensity pulses (Fig. 1). It means that the modern model of the radio pulses propagation through the ISM is not completely correct. On the other hand, we are able to detect the fine structure of the pulsar pulses in the low frequency range that gives us more possibilities to study this phenomenon. The purpose of the present work is to create a model of ISM to explain the deficit of a scattering measure and formation of the fine structure of the pulsar radio emission.

3. Numerical Simulation

The short radio pulses have been generated in a wide frequency range with the pulsar rotation period $P = 1$ sec. The pulses are represented as an amplitude modulated noise signal that has a Gauss shape envelope. The width of the envelope is about 10% of the pulses period. The signal has the uniform distribution of the frequencies in the receiving range $\Delta f = f_H - f_L$ and the uniform distribution of the initial phases in the angles range $[-\pi, \pi]$. The noise signal amplitudes have the Rayleigh distribution. Also the white noise with the normal distribution is added to the propagation channel.

The main idea of the present paper is to create an ISM model that describes the scattering measure deficit. We are taking into account two main factors: the dispersion delay of low frequencies versus high frequencies and the scattering by space irregularities of the electron concentration. We do not consider the Faraday rotation effect.

The dispersion delay of low frequencies versus high frequencies is the result of the relationship between the refraction index and frequency in the cold anisotropic ISM plasma. Using the eikonal equation we write the delay phase $\varphi(\omega)$:

$$\varphi(\omega) \approx \frac{L}{c} - \frac{1}{\omega} \int_0^L N_e(z) dz,$$

where $\omega$ is a cyclic frequency; $e$, $m_e$ are the electron charge and its rest mass; $c$ is the speed of light. $DM = \int_0^L N_e(z) dz$ is the dispersion measure, which characterizes the number of free electrons along the line of sight and is measured in units of pc·cm$^{-3}$.

We can also define the time delay of a frequency $\omega_i$ versus infinity to be able to reduce the dispersion in the received signal. From the equation (3.1): $\Delta \tau_{DM}(DM, \omega_i) = \frac{2\pi e^2}{m_e c} DM \left( \frac{1}{\omega_i} \right)^2$

We also consider the scattering of the pulsar radiation by fluctuations in the concentration of free electrons in the propagation medium along the line of sight. These lead to the amplitude and phase fluctuations of the received wave, called scintillations. To describe the scintillations we use the thin screen model. In this model we consider only phase fluctuations of the original signal that occur in the thin screen that is perpendicular to the line of sight, located halfway the source and observer. The distance between the screen and the observer or the screen and the source must be much greater than the signal wavelength. In this case one could use the eikonal equation. Scattering on the thin screen leads to multibeam interference at the receiver and the point source becomes a finite extended object with angular size equal to the scattering angle $\theta_{sc}$.

The geometric optic approximation gives the scattering angle as a function $\theta_{sc}(\lambda)$ of wavelength: $\theta_{sc}(\lambda) \approx \frac{\Delta x(\lambda) \lambda}{2r_e} = \frac{r_e \delta N_e}{2a^2} \left( \frac{DW}{a} \right)^{1/2}$, where $\lambda$ is the wavelength, $r_e$ is the electron radius, $\delta N_e$ is the fluctuation of the electron concentration, $a$ is the characteristic length scale of the electron-concentration irregularities, and $DW$ is the screen width.
At the receiver the signal passes through a preselector filter. Then, we used the method of dispersion delay removing proposed by Hankins & Rickett (1975). The method uses the eikonal equation to find the argument in the transfer function of the ISM. For the narrow band signal this argument $\Delta \alpha_T(\omega)$ can be expanded in a Taylor series centered at the receiver central frequency $f_0$. The initial phase in the observational reference frame can be written as: $\Delta \alpha_T(\omega) = \frac{2\pi\omega^2}{mc} DM \left( \frac{1}{\omega_i} - \frac{\omega_i^2}{\omega^2} + \frac{\omega_i^4}{\omega^4} - \frac{5\omega_i^6}{\omega^6} + \ldots \right)$

4. Main Results

As a result of the numerical simulation we obtained signal responses at different stages of the modeling. Then we studied the signals by using ACF and spectral analysis. At the sky frequency $f_0 = 20$ MHz the fine structure of the model pulse may be or may not be detected with different parameters of the ISM. The main parameter is the spatial irregularities size of the electron density. The data analysis results are shown in Fig. 2. It is qualitatively similar to real observational data†.

5. Conclusions

1) The presence or absence of the fine structure in the low frequency range is explained by a reaction of radio waves on the propagation in a plasma environment, which is located in the line of sight.

2) The fine structure is smoothed out more strongly by scattering at the large-scale spatial electron density irregularities, at the same time one can detect the fine structure of the pulsar radiation in case of scattering by small-scale irregularities.

3) The characteristic width of the detected fine structure is frequency dependent and increases with decreasing of the radiation frequency.

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† For more details see www.pulsarastronomy.net/IAUS291/download/Posters/IAUS291_UlyanovO_257.pdf
Polarization sounding of the pulsar magnetosphere

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Abstract. The possibility of a polarization sounding of the pulsar magnetosphere is examined, using intrinsic pulsar emission as a probe signal, for modern radio telescopes operating in the meter and decameter wavelength range. Different models of the pulsar magnetosphere at altitudes higher than a radius of critical polarization are used. The propagation medium besides magnetosphere is described by the stratified model, in which each layer has its own density of free electrons and vector of magnetic induction, as well as the spatial and temporal fluctuation scales of these parameters.

The frequency dependence of the polarization parameters of the pulsar radio emission, obtained in the broad band for a selected pulse phase, will enable a sounding deep into the pulsar magnetosphere.

Keywords. Magnetic fields, plasma, polarization, pulsar.

1. Introduction

The pulsar magnetosphere is a region where radio emission is generated. Studying the properties of radio-emitting region is of primary importance for understanding both the nature of pulsar radio emission, and the nature of the neutron star as a whole. There are several models of pulsar magnetosphere, but still there is no unified explanation of physical processes occurring in a pulsar magnetosphere.

The main purpose of this work is to sound the pulsar magnetosphere by studying the polarization properties and characteristics of a pulsar radio emission. The decameter range is the most difficult for polarization studies: there the influence of all known propagation effects becomes apparent with the highest contrast. It is in this range the anomalously powerful pulses from pulsars B0809+74, B0943+10, B0950+08, B1133+16 (Ul'yanov et al. 2006) and the giant pulses from PSR B0531+21 (Popov et al. 2006) are registered.

Furthermore, due to the Faraday effect the bandwidth of intensity modulation of the elliptically polarized radiation in this range narrows down to several tens of kilohertz. It is supposed that this property of radio emission of pulsars (REP) will be used to obtain the polarization parameters of REP via observations on radio telescope UTR-2 which is composed from linearly polarized broadband dipoles. For a moment the observations of REP polarization using this effect were reported for the radio-telescopes DKR 1000 and BCA 100 (Suleymanova & Pugachev 2002). Determination of the polarization parameters requires consideration of both direct and inverse problems. To achieve the assigned task we consider a model of polarized radiation and a model of the propagation medium. Solving the inverse problem allows for the recovery of Stokes parameters in the reference frame of the pulsar using registered REP at the receiver side. In our work the direct and inverse problems are solved as applied to the case of UTR-2 telescope.
2. Model

To solve the assigned task we model a medium of propagation as a layered structure. The most important parts of the propagation medium are the upper pulsar magnetosphere, the interstellar medium (ISM), the interplanetary medium, the Earth’s ionosphere and the underlying surface of a radio telescope. The layers are characterized by their own transmission coefficients and by their own longitudinal and transverse magnetic field components on the line of sight, etc. We assume that propagation of a radiation along a line of sight in each layer is described by a eikonal equation, which includes separate refractive coefficients for the ordinary and extraordinary waves. These coefficients we determine via the mean values of the electron concentration in the selected layer on the line of sight and the average values of magnetic field vector component parallel to the line of sight.

At present stage the propagation of the radio waves in the ISM is considered, since modeling of this medium is the most simple. A radiation point source located at infinitely large distance from the receiving antennas and emitting elliptically polarized radiation in a wide frequency range is considered. We will assume that at distances of a critical radius of polarization the two orthogonal modes of the pulsar radio emission have fixed amplitudes.

Pulsar radiation is modeled by a set of the noise circular frequencies $\omega$ with the Gauss shape of the envelope. In the model we specify a variation of a position angle (PA) $\chi$ along the average profile of the pulse envelope. Influence of the propagation medium is taken into account by eikonal equation $\nabla \varphi(\omega) = n(\omega)\vec{k}(\omega)$, where $\varphi(\omega)$ is the phase of the signal at circular frequency $\omega$, $n(\omega)$ is the ISM refractive coefficient, $\vec{k}(\omega)$ is the wave vector. In this case the equation for the phase of the analytical signal at arbitrary frequency $\omega$ will have the form:

$$\varphi(\omega)_{O,X} \approx \frac{L}{c} - \frac{1}{\omega} \int_0^L N_e(z) dz \mp \frac{1}{\omega^2} \frac{2\pi e^3}{m_e c} \int_0^L N_e(z) \beta(z) dz,$$

(2.1)

where $c$ is the speed of light, $e$ is the electron charge, $m_e$ is the electron rest mass, $L$ is the layer thickness, $N_e(z)$ is the electron concentration on the line of sight, $\beta(z)$ is the value of the projection of the magnetic induction vector onto that line of sight.

The rotation of the polarization plane is connected with the different refraction coefficients for the orthogonal modes that have the opposite directions of rotation. These waves are the so-called ordinary ($O$) and extraordinary ($X$) waves (Zheleznyakov 1997). For $O$ and $X$ waves refractive coefficients can be written as: $n_{O,X} = \sqrt{1 - \omega_p^2/\omega(\omega \mp \omega_H)}$.

Figure 1. a) the dynamic spectrum of the elliptically polarized radiation from PSR B0809+74, detected using UTR-2 ($F_c = 23.7$ MHz, $\Delta F = 1.53$ MHz); b) the Stokes parameters $I, Q, U, V$; c) the position angle $\chi$. 

where \( \omega_p \) and \( \omega_H \) are the plasma and the cyclotron frequencies, respectively, subscripts \( O \) and \( X \) correspond to the ordinary \( (-\omega_H) \) and extraordinary \( (+\omega_H) \) waves.

An example of registering the polarization ellipse of PSR B0809+74 pulse on the radio telescope UTR-2 can be seen in the Fig. 1a. The central recording frequency is \( F_c = 23.7 \) MHz. Period of the Faraday intensity modulation is \( \Delta F_F \approx 20 \) kHz. We have made the simulations for the similar spectra. These spectra were generated for a given value of the rotation measure \( (RM = -234 \text{ rad/m}^2) \) at frequencies \( F_c = 20 \) MHz and \( F_c = 30 \) MHz \( (\Delta F = 4 \) kHz). For the given model signals the Faraday periods of intensity modulation were found. Using these values the magnitude of the rotation measure was estimated. The accuracy of this method is lower than \( 0.5/N_{\text{max}}(f) \), where \( N_{\text{max}}(f) \) is the number of harmonic, which has the maximal intensity. This number depends on \( \Delta F_F \).

3. Results

We can construct a polarization tensor (Zheleznyakov 1997) for a signal registered in two orthogonal polarizations. From polarization tensor the polarization parameters (Stokes parameters) and the variation of PA can be found (see Fig. 1).

In Fig. 1b, the Stokes parameters of the restored signal (the continuous line) and the original signal (dashed line) are presented. The variation of the PA in the pulse window at the receiving end (Fig. 1c) is almost identical to the variation of the model PA. The PA is determined only up to an arbitrary constant.

The developed algorithms were used for processing the real data. For three different anomalously intensive pulses of PSR B0809+74 registered near the center frequency \( F_c = 23.7 \) MHz in the same observation session of one hour duration the variations of the values of the rotation measure of about 1 rad/m\(^2\) were detected. The values of the observed variations are 13 times larger than the errors of determination of the rotation measure values. These variations were observed during nighttime for undisturbed ionosphere. Comparison of the \( RM \) value obtained in the decameter range with \( RM \) values obtained in the 250-500 MHz frequency range (Manchester 1972) allows us to suppose that regular component of the interstellar medium magnetic field and dipole component of the emitting pulsar pole of PSR B0809+74 have opposite directions.

4. Conclusions

The direct and inverse problems of determining the polarization parameters of elliptically polarized signal propagating through ISM were solved by numerical methods. An eikonal equation gives an opportunity to take into account both the Faraday effect and cold plasma influence on the signal properties.

A method of estimating the rotation measure and position angle was proposed. It allows us to recover all Stokes parameters in the reference frame associated with a pulsar.

It was found that ISM magnetic field and visible pulsar magnetic field have opposite directions.

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On the glitch evolution of pulsars

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Abstract. Observation of pulsar glitches remains a powerful tool for studying the interior of neutron stars. Many of the observed glitch properties are shown to result from the evolution of glitches in the different manifestations of neutron stars. Specifically, the type of glitches associated with the Crab and Vela pulsars are explained by this model. We are, also, able to adequately account for the absence, or very low rate, of glitches among the youngest and the very old pulsars.

Keywords. stars: neutron, pulsars: general, pulsars: individual (B1737−30)

1. Introduction

Glitch activity, \( A_g \) (which measures the mean fractional change in period per year owing to glitches), is known to vary with the characteristic age, \( \tau_c \), of pulsars. We note, however, that \( \tau_c \) may not give a reliable estimate of the true pulsar age in some cases. Glitch activity is a function of the size and interval (frequency) of glitches in a pulsar. Youthful pulsars with \( \tau_c \sim 10^4 \)–\( 10^5 \) yr are known to have very high \( A_g \) while younger and older ones are characterized by lower \( A_g \). Urama & Okeke (1999) observed that the glitch activity of the young and youthful pulsars generally increases with the logarithm of the spin-down rate with the exception of the Crab pulsar (younger than \( 10^4 \) yr) which was considered to have “unusual” glitch behaviours (McKenna & Lyne, 1990).

However, with over four decades of pulsar timing and more than 600 reported glitches (large and small) in the conventional radio pulsars, binary pulsars, millisecond pulsars, AXPs, and other manifestations of neutron stars (some of these being younger than radio pulsars), we have re-examined the relationship between some of the pulsar glitch parameters.

2. Pulsar age, glitch size, interval and evolution

Nearly 600 macro and micro glitches have been reported in about 130 pulsars (see e.g Chukwude & Urama 2010; Espinoza et al. 2011). The distribution of the glitches shows that there is a predominance of small glitches for \( \tau_c \sim 10^5 \) yr and \( \tau_c < 5 \times 10^3 \) yr; and no large glitch has been reported for \( \tau_c > 10^7 \) yr. The preponderance of very small glitches for older pulsars may account for the non-observance of glitches for pulsars with \( \tau_c > 10^8 \) yr.

To study the complex relationship between pulsar characteristic age and the size and interval of her glitches, we selected 10 pulsars with a record of at least 4 glitches of jump magnitudes \( \Delta \nu/\nu \gtrsim 10^{-8} \). Three of these pulsars are younger than \( 10^5 \) yr, while the rest are youthful pulsars (\( \tau_c \sim 10^4 \)–\( 10^5 \) yr). From a plot of the average glitch interval, \( \tau_g \), and
On the glitch evolution of pulsars

3. Glitch size evolution in PSR B1737–30

PSR B1737–30 (J1740–3015) belongs in the group of youthful pulsars ($\tau_c \sim 10^4 - 10^5$ yr), known for undergoing frequent large glitches. With an average of about 1.3 glitches per year, PSR B1737–30 is one of the most frequently glitching pulsars of the ~2000 known pulsars. This pulsar has a somewhat, uniform distribution of large and small glitches. Fig. 2 shows the magnitudes and distribution of the glitches with time.

One prominent feature of Fig. 2 is a linear increase in the magnitudes of the large glitches ($\Delta \nu/\nu \geq 5 \times 10^{-7}$) observed in this pulsar. This could be an indication that different mechanisms are responsible for the large and small glitches; and that these different glitches evolve differently as shown in Fig. 1. This may actually be the best evidence of a growth in the glitch size in pulsars.

4. Discussions and conclusion

Our result provides a natural explanation for the very frequent large ($\Delta \nu/\nu \sim 10^{-6}$) and super-large ($\Delta \nu/\nu \geq 10^{-5}$) glitches exhibited by very young pulsars. Frequent large and super-large glitches are expected only from pulsars in the age range $\tau_c \sim 10^2 - 10^{3.5}$ yr. It is, therefore, not a surprise that the following youthful ($\tau_c \sim 10^4 - 10^5$ yr) pulsars have
only one super-large glitch each: CXO 1647−4552 ($\Delta \nu/\nu = 65 \times 10^{-6}$) and B1856+0113 ($\Delta \nu/\nu = 11.6 \times 10^{-6}$). At such ages, the frequency of such super-large glitches could range from $\sim 20 - 100$ yr.

A growth in glitch size, similar to the one observed in PSR B1737−30 has also been noticed on the “larger” ($\Delta \nu/\nu \geq 3 \times 10^{-8}$) Crab pulsar glitches. And these 3 “larger” Crab pulsar glitches are separated by exactly 14.5 yr (5300 d) each. If such glitch size growth continues, Crab pulsar glitch sizes of $\Delta \nu/\nu \sim 10^{-6}$ should be expected in the next 100 yr. None of the other frequently glitching radio pulsars (with a record of at least 6 glitches of sizes $\Delta \nu/\nu \geq 10^{-8}$) show such linear growth in jump magnitude. However, these frequently glitching radio pulsars are already undergoing very large glitches ($\Delta \nu/\nu \sim 10^{-6}$), implying that the glitch size may have stopped growing. However, these pulsars are younger than, or of comparable age to, PSR B1737−30 and, therefore, it could be difficult to understand why the glitch magnitude should still be growing in B1737−30. The Crab pulsar is still very young ($\tau_c = 1.2$ kyr) compared to these frequently glitching radio pulsars and the glitch size is usually explained in terms of its high interior temperature.

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References

Quadrupole moments of rotating compact stars

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Abstract. We present quadrupole moments of rotating neutron and strange stars calculated using standard Hartle Thorne approach. We demonstrate differences between neutron and strange star parameters connected with quadrupole moments and how this parameters could be, in the case of neutron stars, approximated almost independently on neutron star equation of state.
Particle simulation for an axisymmetric pulsar magnetosphere

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Abstract. We developed a new particle simulation code which includes pair creation (magnetic pair creation and photon collision process), propagation of gamma-ray, inertia of particle, interaction of plasma and multi-pole stellar field for steady axisymmetric pulsar magnetosphere. The photon path is solved stochastically by an analytical solution of the mean free path of pair creation processes at the photon position. The superimposed quadrupole magnetic field forms asymmetric electrostatic clouds on the poloidal plane and the accelerating region is different from the dipole case. Here, we demonstrate some results of a test run for our simulation. We will adopt the code for more complicated cases, such that all above-mentioned effects will be considered together in future work.

Keywords. pulsars: general, plasmas

1. Introduction

A highly magnetized and rapidly rotating neutron star is an accelerator for charged particles. Such a star becomes a unipolar dynamo. The plasma is accelerated by the induced electric field and emits gamma-rays by bremsstrahlung. Successively, the gamma-ray photon converts into an electron-positron pair which forms an outflow of plasma with a relativistic kinetic energy (i.e., the pulsar wind) and is a persistent energy source of the surrounding synchrotron nebula. Where, and why, these particles are accelerated in the pulsar magnetosphere is a longstanding problem.

The gamma-ray pulsations at the rotation period mean the local accelerating region co-rotates with star, and that there should be a region of plasma deficiency. Recent observations by the Fermi Gamma-ray Space Telescope have promoted an understanding of the emission from gamma-ray pulsars (Abdo et al. 2010). Although some conventional gap models had been discussed phenomenologically, recent observation of gamma-ray pulsar indicates an outer gap (Cheng et al. 1986ab) is the origin of the high energy photons (Abdo et al. 2009c).

We reported a steady solution where outflow of plasma and outer gaps coexist (Wada & Shibata 2007, 2011). But the artificial treatment of pair creation made large gaps in middle latitudes for the solution. For detailed discussion of the structure of magnetosphere, more realistic treatment of pair creation was needed. That is, the mean free path of gamma-ray and energy dependence of photon for path should be considered. We have further developed our simulation code to work out the problem for our previous work.
2. Outline of particle simulation

In this paper, because we consider the case of dipole plus quadrupole magnetic field with the star. Then stellar magnetic field is written by

\[ B = B_{\text{dip}} + B_{\text{quad}}, \]  

(2.1)

\[ B_{\text{dip}} = B_0 \frac{R_0^3}{r^3} \cos \theta e_r + \frac{B_0}{2} \frac{R_0^3}{r^3} e_\theta, \]  

(2.2)

\[ B_{\text{quad}} = B_2 \frac{R_0^4}{r^4} (3 \cos^2 \theta - 1) e_r + B_2 \frac{R_0^3}{r^3} \sin \theta \cos \theta e_\theta. \]  

(2.3)

Where \( e_r \) and \( e_\theta \) are unit vectors in spherical coordinates and \( r, \theta, R_0, B_2 = \delta B_1 \) indicate distance from origin, colatitude, stellar radius and magnetic field intensity on the pole, respectively. \( \delta \) taken to be a constant in our model.

We assume pulsar is perfect conductive sphere and force-free condition on the stellar surface. Such as

\[ E(R_0, \theta) = -\frac{R_0 \sin \theta \Omega_0}{c} e_\phi \times B(R_0, \theta). \]  

(2.4)

Where, \( \Omega_0 \) is stellar angular velocity and \( e_\phi \) is unit vector for azimuthal direction. The induced electric field is calculated by the solution of Laplace equation with the boundary condition (2.4). They are written by

\[ E = E_{\text{mono}} + E_{\text{quad}} + E_{\text{oct}}. \]  

(2.5)

\( E_{\text{quad}} \) and \( E_{\text{oct}} \) are induced by dipole and quadrupole magnetic field, respectively. We demonstrate particle simulation in which charge of plasma is given by \( q \) in steady state. And therefore, the static electro-magnetic field formed by magnetospheric charge and current are given by

\[ E_q = \sum_{i=1}^{n} q_i \left[ \frac{r - r_i}{|r - r_i|^3} - \frac{R_0}{r_i} \frac{r - (R_0/r_i)^2 r_i}{|r - (R_0/r_i)^2 r_i|^3} - \left( 1 - \frac{R_0}{r_i} \right) \frac{r}{r_i^3} \right], \]  

(2.6)

\[ B_q = -\sum_{i=1}^{n} \frac{q_i \times (r_i - r)}{|r_i - r|^3}. \]  

(2.7)

Where subscripts \( i \) represent \( i \)-th particle and \( r \) is position vector. We can calculate the interaction between plasma rapidly, with using special purpose programmable computer GRAPE-DR. Relativistic equation of motion of plasma is written by,

\[ m_i \frac{d}{dt} \gamma_i n_i = q_i \left( E_i + \frac{v_i}{c} \times B_i \right) + f_{\text{rad},i}. \]  

(2.8)

Where, \( m, v, f_{\text{rad}} \) are mass, velocity, radiation drag force for particle, respectively. The outline of our particle simulation is as follows.

(a) Start the calculation from the vacuum condition.

(b) Replace the surface charge density with simulation particle.

(c) Compute the electromagnetic field at the particle positions.

(d) Renew the position and velocity of particle with equation of motion.

(e) Create gamma-ray photon where \( E_\parallel > E_{\text{cr}} \).

(f) Compute the position where gamma-ray convert into pair and insert plasma at the position

(g) Go back to step (2), unless the steady state is established.

Where \( E_\parallel \) is intensity of electric field along the magnetic field and \( E_{\text{cr}} \) is critical field.
intensity that we just consider parameter for pair creation in current model. We choose pair creation processes; magnetic pair creation and photon collision process (Thermal X-ray photon from stellar surface and gamma-ray photon by curvature radiation). The pair creating position is calculated stochastically by mean free path of analytical solution of the pair creation processes is calculated by in numerical simulation.

3. Result

We carried out test run for our simulation code with magnetic pair creation dominant case (A), photon collision process dominant case in dipole stellar magnetic field and quadrupole field dominant case in dipole stellar magnetic field (See Fig. 1 and 2). Panels A and B show that the pair creating position is different for each pair creation process. For $\delta = 2$, C shows outer gap structure is changed compared with pure dipole case. These simulations were carried out just in one rotation period. Although these solutions are quasi-steady, longer-running simulations are needed to obtain steady solution.

![Figure 1](image1.png)

Figure 1. Distribution of particle on the poloidal plane; left panel is (A) and right panel is (B), red and orange dots are positive particle and blue and cyan dots are negative particle, respectively. Green line is light cylinder.

![Figure 2](image2.png)

Figure 2. Left panel; green line is path of gamma-ray, yellow dot is gamma-ray emitting region and magenta dot is pair creating point, respectively. Right panel; distribution of particles on the poloidal plane, for quadrupole field dominant case in dipole stellar magnetic field (C).

References

Wave propagation in pulsar magnetospheres

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Abstract. We study the propagation effects of radio waves in a pulsar magnetosphere, composed of relativistic electron-positron pair plasmas streaming along the magnetic field lines and corotating with the pulsar. We critically examine the various physical effects that can potentially influence the observed wave intensity and polarization. We numerically integrate the transfer equations for wave polarization in the rotating magnetosphere, taking account of all the propagation effects in a self-consistent manner. For typical magnetospheric plasma parameters produced by pair cascade, we find that the observed radio intensity and polarization profiles can be strongly modified by the propagation effects. Some applications of our results are discussed.

Keywords. pulsars: general, plasmas, polarization, magnetic fields, radiative transfer

1. Introduction

Pulsar radio emission is likely generated within a few hundred kilometers from the neutron star (NS) surface (e.g. Cordes 1978; Blaskiewicz et al. 1991; Kramer et al. 1997; Kijak & Gil 2003). A pulsar is surrounded by a magnetosphere filled with relativistic electron-positron pair plasmas (plus possibly a small amount of ions) within the light cylinder. When radio waves propagate through the magnetosphere, the total flux, polarization state and spectrum of the emission may be modified by propagation effects.

Wave propagation effects in pulsar magnetospheres play an important role in the diverse behavior of pulsar polarization, such as the origin of circular polarization (CP) and orthogonal polarization modes (OPM) – see, e.g., Lyubarsky 2008 for a review. A number of theoretical works have been devoted to study how magnetosphere propagation influences pulsar polarization observations (Cheng & Ruderman 1979, Arons & Barnard 1986, Barnard & Arons 1986, Lyubarskii & Petrova 1998, Luo & Melrose 2001, Petrova 2006). However, none of the previous studies have calculated the final polarization profiles with all of these propagation effects included in a self-consistent way within a single theoretical framework. It is often unclear which of the effects are most important, and if so, under what conditions. In our works (Wang, Lai & Han 2010, hereafter WLH10), we attempt to combine all the propagation effects, evaluate their relative importance, and use numerical integration along the photon ray to study the influence of propagation effects on the final polarization states.

2. Some typical propagation effects

Adiabatic walking (Cheng & Ruderman 1979). If the plasma properties change very slowly and the mode evolution is adiabatic, the two natural wave modes will propagate independently. For example, an initially O-mode photon will always stay in O-mode, which means its polarization direction follows the magnetic field plane along the ray.
Wave mode coupling. When a photon propagates through the magnetosphere to outside space, mode evolution will become non-adiabatic at a position called the “polarization-limiting-radius” \((r_{pl})\). Near the radius, the two natural wave modes will be coupled, CP can be generated. Away from the radius, the polarization state will be frozen and not change again.

Quasi-tangential effect (Wang & Lai 2009). When the photon crossed the region where its wave vector is aligned or nearly aligned with the magnetic field, the azimuthal angle of the magnetic field changes quickly, and mode coupling may occur. This effect only works for small impact angles.

Circularization. If the wave vector is very close to the magnetic axis, or the pair plasma is asymmetric, the natural wave modes could become circular polarized near the polarization-limiting-radius. Thus, even if the photon is initially 100% linearly polarized, the final polarization state is determined by the natural wave modes near \(r_{pl}\), which may be partially circularly polarized.

Cyclotron absorption. The emission will be absorbed near the cyclotron resonance where the wave frequency in the plasma rest frame is close to the cyclotron frequency.

3. Numerical integration of wave propagation in magnetosphere

In many cases these different propagation effects are coupled and not easy to separate. Thus, to produce the observed polarization profiles, it is necessary to use the numerical ray integrations to calculate the final wave polarization states.

Polarization evolution for a single ray. We choose a typical emission height \(r_{em} = 50R_\ast\) and assume that at the emission point, the photon is polarized in the magnetic field line plane (O-mode). We can calculate the dielectric tensor at each point along the photon ray, and integrate the wave evolution equation (see Eq. 2.10 of WLH10) from the emission point to a large radius (generally close to the light cylinder \(r_{lc}\)), and get the final polarization state of the photon. It is clear that wave mode coupling and cyclotron absorption are the most obvious effects for all the cases.

Polarization Profiles of Pulsar Emission Beam. Assuming that emission at various pulsar rotation phases are from the same height, we can extend the single ray evolution results to the polarization profiles of pulsar emission beam after the propagation effects in pulsar magnetosphere. Figure 1 shows a typical example of the phase evolution of the intensity and polarization. We find the intensity and polarization profiles are strongly affected by the propagation effects, such as:

1) The intensity profile is modified by phase-different cyclotron absorption, the trailing side being absorbed more.

2) The PA curve is close to RVM only when the impact angle is not so small, and Lorentz factor and plasma density are not so large. There exits a shift away from the RVM predicted curve (Fig. 1a), which is \(r_{pl}/r_{lc}\).

3) For a large Lorentz factor and plasma density, or very small impact angles, the PA curve is more complicated and deviates far away from the RVM predictions (Fig. 1b-d). In some cases, the observed PA curve has a 90° jump accompanied by the maximum CP (Fig. 1b), which may be a possible origin of orthogonal polarization modes in some pulsars. The circular polarization curve could have sign reversals in this case.

4. Conclusions

We use numerical integration of the photon polarization along the ray to incorporate all these propagation effects in magnetosphere self-consistently within a single frame-
Figure 1. Intensity and polarization profiles of pulsar emission beam. The four columns correspond to four fixed impact angles $\chi = -5^\circ, -1.9^\circ, -1^\circ$ and $-0.5^\circ$, respectively. The horizontal axis $\Psi_i$ is the pulsar rotation phase. In each column, we plot the Stokes parameters $I/I_0$ (top panel), $V/I$ (second panel), $V/I$ (third panel), $\phi_{PA}$ and $\phi_B$ (bottom panel, the solid line for $\phi_{PA}$ and the dashed for $\phi_B$). The initial polarization states are all ordinary mode, and the other parameters are: surface magnetic field $10^{12} \text{G}$, NS spin period $P = 1 \text{s}$, wave frequency $\nu = 1 \text{GHz}$, Lorentz factor $\gamma = 100$, inclination angle $\alpha = 30^\circ$, and emission height $r_{em} = 50R_*$. We find that, for typical parameters of the magnetospheric plasma produced by pair cascade, the final intensity and polarization position angle can be strongly modified by the propagation effects. Although we adopted the simplest (and minimum) assumptions about the property of the magnetospheric plasma and the intrinsic radio emission mechanism, our results already show great promise in explaining a number of otherwise puzzling observations, such as the phase-shift of PA curve, CP origin, orthogonal mode polarization. An interesting application is that for the so-called conal double type pulsars, which in our model corresponds to large impact angle $\chi$, the relationship between the single sign of the circular polarization and the derivation of $\phi_{PA}$ (see Han et al. 1998) can be easily understood if CP is generated by wave mode coupling effect.

References
Search for the gravitational wave memory effect with the Parkes Pulsar Timing Array

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Abstract. Gravitational wave bursts produced by supermassive binary black hole mergers will leave a persistent imprint on the space-time metric. Such gravitational wave memory signals are detectable by pulsar timing arrays as a glitch event that would seem to occur simultaneously for all pulsars. In this paper, we describe an initial algorithm which can be used to search for gravitational wave memory signals. We apply this algorithm to the Parkes Pulsar Timing Array data set. No significant gravitational wave memory signal is founded in the data set.

Keywords. gravitational waves, pulsar, black holes.

1. Introduction

It is believed that observations of MSPs will lead to the direct detection of gravitational waves (GWs) with frequencies of $10^{-9} – 10^{-7}$ Hz (Hobbs et al. 2005, Jenet et al. 2005). Many observing projects have now been started with the goals of observing a large enough sample pulsars with sufficient precision to detect GW signals. Such projects are known as pulsar timing arrays (PTAs, Foster 1990). Here we make use of data set from the Parkes Pulsar Timing Array project (PPTA; Manchester et al. 2012). The Parkes observations have already been used in searching for the GW emission from individual, non-evolving, supermassive black hole binaries (Yardley et al. 2010), placing an upper limit on a background of GWs (Jenet et al. 2006) and in attempting to detect such a GW background (Yardley et al. 2011).

In contrast to earlier searches for GWs using the PPTA data sets, in this paper, we focus on the GW memory (GWM) phenomenon. The expected source is a supermassive binary black hole (SMBBH) system that has coalesced (Favata 2009). At the coalescence stage of the SMBBH, a permanent change in the space-time metric will be induced. Cordes & Jenet (2012) and van Haasteren & Levin (2010) have previously shown that pulsar timing arrays are sensitive to such GW memory events. When such a GW signal passes a pulsar or the Earth, it will lead to a simple frequency jump in the observed pulse frequency of the pulsar. The timing residuals will have the characteristics of a simple glitch event. GW memory events passing a single pulsar will lead to a glitch-like event in the timing residuals of that pulsar only. GW memory events passing the Earth will lead to a glitch-like event seen in the timing residuals of all pulsars with the size of
the pulse frequency jump depending upon the GW source-Earth-pulsar angle. The pre-fit timing residuals induced by the GWM signal that occurred at \(t = t_0\) can be written as:

\[
r(t)_{\text{prefit}} = \frac{1}{2} h_{\text{mem}} (1 - \cos \theta) \cos 2\phi (t - t_0) \Theta (t - t_0),
\]

In the above, \(\theta\) is the GW source–Earth–pulsar angle, \(\phi\) is the angle between the wave’s principle polarization and the projection of the pulsar onto the plane perpendicular to the propagation direction, and \(h_{\text{mem}}\) is the amplitude of the GWM signal. Therefore, the pre-fit timing residuals induced by the Earth term of GWM signal will give rise to a linear increase of the pre-fit residuals with time.

2. Method

Here we describe our current algorithm and present initial results. The completed algorithm and our final results will be published elsewhere. We have updated the TEMPO2 pulsar timing model to include the effect of a GWM event. The position of pulsars and the GW source are specified in the equatorial coordinate system by their right ascension and declination (\(\alpha, \delta\)). The principle polarisation of GW is defined in a coordinate system \((r_g, \alpha_g, \delta_g)\) where the GW propagates along the \(-r_g\) direction (See Fig. 1 of Hobbs et al. 2009). Since TEMPO2 only implements a linear least-squares-fitting procedure for improving the pulsar timing model, TEMPO2 can only be used to fit for the amplitude of the GWM event. If, as usual, the position, epoch and/or polarisation angle is unknown and it is necessary to determine these parameters using a different procedure. A global fitting algorithm (first described in Champion et al. 2010) is used to fit for pulse, astrometric and orbital parameters of each pulsars individually whilst simultaneously fitting for \(h_{\text{mem}}\). In order to account for the unknown polarisation angle (PA) we carry out two fits, one with \(PA = 0\) and the second with \(PA = \pi/4\). For each fit we obtain a measurement of \(h_{\text{mem}}\) (\(h_1\) and \(h_2\) for \(PA = 0\) and \(PA = \pi/4\), respectively) and their corresponding uncertainties (\(\sigma_1\) and \(\sigma_2\) respectively). Then we form the following detection statistic:

\[
S = \left( \frac{h_1}{\sigma_1} \right)^2 + \left( \frac{h_2}{\sigma_2} \right)^2
\]

Coles et al. (2011) discussed the issues arising from fitting a pulsar timing model in the presence of non-white noise. For this work, we obtain a simple analytic model of the red noise for each pulsar (as described in Manchester et al. 2012) and use the generalised least-squares-fitting routines (often referred to as “Cholesky” fitting) within TEMPO2.

3. Observations

We make use of the Parkes Pulsar Timing Array (PPTA) data set which is described in Manchester et al. (2012). These data include regular observations of 20 millisecond pulsars at intervals of 2-3 weeks from 2005 to 2011. All observations were taken with the Parkes 64-m radio telescope. The typical integration time for each pulsar is about 1 hr. Most of the timing offsets between the different observing systems have been removed. However, some of the arbitrary jumps from the timing model included in the Verbiest et al. (2008, 2009) were retained (Manchester et al. 2012). Variations of dispersion measure were corrected by using multi-frequency observations. Timing residuals were formed using the TEMPO2 software package (Hobbs et al. 2006) making use of the JPL DE421 Solar System ephemeris (Folkner et al. 2008) and refered to terrestrial time as realised by BIPM2011.
4. Results

We searched for a GWM signal using the algorithm described above. The measured statistic value ranges from 0 to 20 for different trial positions and glitch epochs. By comparison, the largest detection statistic value is \( \sim 126 \) after a small simulated GWM signal is added into the PPTA data set. We therefore conclude that there is not a large GWM signal in the PPTA data set. We are now carrying out statistical tests of the algorithm in order to answer the following questions: “what is the largest GWM signal that could be present in our data?” and “what is the probability that we have already made a detection of a small GWM signal?” These statistical tests are not yet complete, but are based on Monte-Carlo simulations in which we inject small GWM signals into simulated data sets and measure the detection statistic values.

It is unlikely that we will make a detection of a GWM event with the existing Parkes data set. However, the data sets continue to get longer and future analyses are likely to be carried out with a combination of data from different observatories Worldwide. In the longer term, it is expected that future telescopes such as FAST, Urumqi 110-m and the SKA Phase I will provide data sets in which GWM events will be easily detectable.

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The distance indicators in gamma-ray pulsars

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Abstract. Distance measurements of gamma-ray pulsars are challenging questions in present pulsar studies. The Large Area Telescope (LAT) aboard the Fermi gamma-ray observatory discovered more than 100 gamma-ray pulsars, including 34 new gamma-selected pulsars which nearly have no distance information. We study the relation between gamma-ray emission efficiency ($\eta = L_\gamma/\dot{E}$) and pulsar parameters, for young radio-selected gamma-ray pulsars with known distance information. We have introduced three generation order parameters to describe gamma-ray emission properties of pulsars, and find a strong correlation between $\eta$ and $\zeta_3$, the generation order parameter which reflects $\gamma$-ray photon generations in pair cascade processes induced by magnetic field absorption in pulsar magnetosphere. A good correlation between $\eta$ and $B_{LC}$, the magnetic field at the light cylinder radius, is also found. These correlations can serve as distance indicators in gamma-ray pulsars, to evaluate distances for gamma-selected pulsars. Distances of 35 gamma-selected pulsars are estimated, which could be tested by other distance measurement methods. The physical origin of the correlations may be also interesting for pulsar studies.

Keywords. gamma rays: general – pulsars: general – stars: neutron

1. Introduction

The distance measurement of pulsars is always a difficult problem in pulsar studies. Trigonometric parallax measurements of radio pulsars are the reliable method, but are only available for the nearby pulsars (< 0.4 kpc). The most common way to obtain radio pulsar distance is based on the computation from dispersion measurement (DM) coupled to an electron density distribution model like NE 2001 model (Cordes & Lazio 2002). The pulsar distance can be also estimated from kinematic model: the distance of possible associated objects (supernova remnants, star clusters, or HII regions) could be measured from Doppler shift of absorption or emission lines in HI spectrum together with the rotation curve model of the Galaxy. The distance of some pulsars with X-ray emissions can be estimated from X-ray observations of the absorbing column or from correlations in X-ray luminosities versus spin-down power or photon index (Gotthelf 2003; Wang 2009). These methods may be available for radio or X-ray pulsars, but for gamma-selected pulsars if no possible associated objects, we would have no any information on their distance.

Presently more than 100 gamma-ray pulsars are discovered by the Fermi/LAT, including 35 gamma-selected pulsars. Distance information for these gamma-ray pulsars is important for pulsar physics studies. Based on the EGRET pulsars, Thompson et al. (1999) found a possible correlation of $L_\gamma \propto E^{1/2}$. For the larger sample of gamma-ray pulsars (Abdo et al. 2010), the young pulsars looks to still follow this relation with a large scattering factors of more than 10. Thus a better correlation in gamma-ray pulsars should be probed for distance estimate for gamma-ray pulsars.
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Table 1. The estimated distances of 35 gamma-selected pulsars. d1−2 denotes the distance
calculated from relations of η − ζ3 and η − BLC , respectively. d3 is the estimated distance from
other methods with references provided.
Pulsar
J0007+7303
J0106+4855
J0357+32
J0622+3749
J0633+0632
J0633+1746
J1418-5819
J1459-60
J1620C4927
J1732-31
J1741-2054
J1746C3239
J1803C2149
J1809-2332
J1813-1246
J1826-1256
J1836+5925
J1838-0537
J1907+0602
J1958+2846
J2021+4026
J2028+3332
J2030+4415
J2032+4127
J2238+59
J1023-5746
J1044-5737
J1413-6205
J1429-5911
J1846+0919
J1954+2836
J1957+5033
J2055+2500
J2111+4606
J2139+4716

P
s
0.316
0.083
0.444
0.333
0.297
0.237
0.111
0.103
0.171
0.197
0.414
0.2
0.106
0.147
0.048
0.110
0.173
0.146
0.107
0.290
0.265
0.177
0.227
0.143
0.163
0.111
0.139
0.110
0.116
0.226
0.093
0.375
0.320
0.158
0.282

Ṗ
Fγ (> 100 MeV)
s s−1
erg cm−2 s−1
3.61×10−13
3.82×10−10
4.3×10−16
2.4×10−11
1.20×10−14
6.38×10−11
2.5×10−14
1.69×10−11
7.95×10−14
8.00×10−11
1.10×10−14
3.38×10−9
1.70×10−13
2.35×10−10
2.55×10−14
1.06×10−10
−14
1.0×10
1.35×10−10
2.62×10−14
2.42×10−10
1.69×10−14
1.28×10−10
6.6×10−15
7.86×10−11
1.9×10−14
1.31×10−10
−14
3.44×10
4.13×10−10
1.76×10−14
1.69×10−10
1.21×10−13
3.34×10−10
1.49×10−15
5.99×10−10
4.6×10−13
1.75×10−10
8.68×10−14
2.75×10−10
2.10×10−13
8.45×10−11
−14
5.48×10
9.76×10−10
4.9×10−15
6.09×10−11
6.5×10−15
7.06×10−11
1.98×10−14
1.11×10−10
9.86×10−14
5.44×10−11
−13
3.84×10
2.69×10−10
5.46×10−14
1.03×10−10
2.78×10−14
1.29×10−10
3.05×10−14
9.26×10−11
9.92×10−15
3.58×10−11
2.12×10−14
9.75×10−11
7.08×10−15
2.27×10−11
−15
4.08×10
1.15×10−10
1.4×10−13
4.13×10−11
1.8×10−15
2.51×10−11

d1
kpc
0.86+0.30
−0.32
0.92+0.33
−0.35
+0.25
0.72−0.29
2.33+0.73
−0.65
1.26+0.41
−0.48
0.19+0.07
−0.07
1.39+0.58
−0.57
+0.70
1.76−0.67
0.790.35
−0.34
0.77+0.41
−0.35
0.59+0.26
−0.25
0.75+0.27
−0.30
+0.43
1.01−0.49
0.78+0.31
−0.31
2.18+0.71
−0.64
1.29+0.56
−0.44
0.32+0.13
−0.14
2.18+0.74
−0.69
1.39+0.46
−0.40
+0.56
1.54−0.51
0.38+0.20
−0.21
0.80+0.32
−0.31
0.76+0.30
−0.30
1.32+0.49
−0.52
+0.75
2.36−0.70
1.77+0.70
−0.55
1.72+0.60
−0.65
2.52+0.89
−0.92
1.84+0.64
−0.69
+0.55
1.52−0.70
1.90+0.67
−0.80
1.22+0.41
−0.45
0.56+0.19
−0.23
2.79+0.90
−1.01
0.81+0.32
−0.31

d2
drf
reference
kpc
kpc
+0.72
1.18−0.44
1.4±0.3 Pineault et al. 1993
1.25+0.76
−0.52
0.73+0.51
−0.30
2.73+1.21
−0.89
+0.76
1.37−0.60
+0.12
0.17+0.09
0.25−0.06
Faherty et al. 2007
−0.06
1.86+1.09
2-5
Ng et al. 2005
−0.80
1.62+0.97
−0.69
+0.58
0.97−0.35
+0.49
0.86−0.30
0.80+0.48
−0.29 0.38±0.11 Camilo et al. 2009
1.06+0.62
−0.42
1.42+0.91
−0.60
0.81+0.48
1.7±1.0 Oka et al. 1999
−0.30
+1.21
1.56−0.68
1.39+0.86
−0.60
0.27+0.15
< 0.8
Halpern et al. 2007
−0.09
2.62+1.31
−0.90
1.42+0.95
−0.61
1.86+1.01
−0.78
0.46+0.20
1.5 ± 0.5 Landecker et al. 1980
−0.18
1.17+0.59
−0.52
1.03+0.55
−0.50
1.33+0.71
1.6 − 3.6 Camilo et al. 2009
−0.50
+1.36
2.64−0.93
2.09+0.95
−0.88
1.86+0.86
−0.72
1.56+1.12
−0.60
1.79+0.97
−0.70
+0.80
1.44−0.51
1.72+1.10
−0.71
1.31+0.65
−0.37
0.61+0.30
−0.19
3.70+1.51
−1.70
1.08+0.54
−0.50

2. Distance Indicators in Gamma-ray Pulsars
Gamma-ray emission eﬃciency (η = Lγ /Ė) is an important parameter in gamma-ray
pulsars, which varies for diﬀerent populations of pulsars. With the gamma-ray pulsar
sample with distance information, we have studied the possible relations between the
eﬃciency and some pulsar parameters, like spin period, age, magnetic ﬁeld at light cylinder (BLC ), and three generation order parameters (ζ1−3 , see details in Wang & Zhao
2004). We found that there exist strong correlations between η and BLC and ζ3 (Wang
2011). With these correlations, we have a possible way to estimate a reliable distance for
gamma-ray pulsars with only known P , Ṗ and Fγ .
We use the distance indicators obtained by η − ζ3 , BLC correlations to estimate the
distances of the 35 gamma-selected pulsars which nearly have no other distance information (Table 1). The evaluated distances by η − ζ3 and η − BLC correlations are similar,
suggesting that two distance indicators can be checked by each other.
The distance of some gamma-selected pulsars was also estimated by other methods,
which can compared with our estimate. For the Geminga pulsar, we estimate the distance
of 0.19±0.07 kpc which is well consistent with the distance value of 0.25+0.12
−0.06 kpc from the


optical trigonometric parallax measurement (Faherty et al. 2007). For PSR J1836+5925, we estimate its distance as $\sim 0.3$ kpc (corresponding to an efficiency of $\sim 55\%$) which is also well below the upper limits of 0.8 kpc according to its thermal X-ray spectrum (Halpern et al. 2007). For other gamma-selected pulsars, our estimated distance values are generally below those from other methods, but may be more reliable with the gamma-ray efficiency $\eta$ generally below 1.

Fig 1. shows the distance distributions of three classes of gamma-ray pulsars: gamma-selected pulsars, radio-selected pulsars and millisecond pulsars. The distances of gamma-selected pulsars are provided by the distance indicator of the $\eta - \zeta_3$ relation. Gamma-ray loud millisecond pulsars distribute at a distance peak around 0.3 kpc because MSPs generally have lower spin-down powers. Gamma-selected young pulsars distribute at the distance peak of $\sim 1.2$ kpc, while radio-selected young pulsars distribute at the distance peak of $\sim 2.5$ kpc. This difference in distance distributions for two classes of gamma-ray young pulsars may involve further interest. The nearby unresolved radio-quiet gamma-ray pulsars could contribute to diffuse gamma-ray/positron background specially for the high-latitude pulsars located in the Gould Belt (Wang et al. 2005).

References
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On the mode switching timescales of pulsar PSR B0329+54

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Abstract. Chen et al. (2011) found that the durations (timescales) of the normal and abnormal modes of PSR B0329+54 follow a gamma distribution, and constrained the parameters of the distribution function. In this paper, we perform a further analysis on the relationship between the timescales of the two modes. The ratio between the durations of a normal mode and the succeeding abnormal mode is calculated for 54 such pairs. It is found that the cumulative distribution function (CDF) of the ratio is consistent with the CDF obtained by assuming random mode switching, suggesting that the two modes work independently.

Keywords. Pulsars, emission mechanism, mode switching

1. Introduction

The mode switching phenomenon has been observed in a few tens of pulsars. The pulse profile, polarization and the radio spectra of profile components change when the mode switches. It is known that the duration of mode can range from tens of rotating periods to tens of days (Lyne et al. 2010). However, the statistical property of the mode durations has been unknown for a long time because of limited observations. Thanks to the two 8-day continuous observations to PSR B0329+54 in March 2004 with the 25m radio telescope at Xingjiang Astronomical Observatory (XAO), and the daily monitoring data with 15m telescope at Jodrell Bank Observatory (JBO), Chen et al. (2011), for the first time, identified the statistical distribution of mode duration for this pulsar. It was found that both the timescales of the normal and abnormal modes follow gamma distributions, i.e. the probability distribution function (PDF) \( \propto t^{k-1}e^{-t/\tau} \), where the shape parameter \( k \) is \( 0.75^{+0.22}_{-0.12} \) for the normal mode and \( 0.84^{+0.28}_{-0.22} \) for the abnormal mode, and the typical timescales \( \tau \) are \( 154^{+41}_{-36} \) and \( 31.5^{+8.0}_{-5.5} \) minutes for the normal and abnormal modes, respectively. Since the shape parameters are similar, the major difference between their distribution is the typical timescale, of which the normal mode is much longer than the abnormal mode. One may ask a further question: is there any correlation between the durations of succeeding normal and abnormal modes, e.g. a tendency that a longer abnormal mode follows a longer normal mode, or are durations just random? In this paper, we present further results regarding this question.

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2. Results

Using the data of mode duration used in Chen et al. (2011), we calculate the ratio between the durations of a normal mode ($t_n$) and the succeeding abnormal mode ($t_a$), $\eta = t_n/t_a$. A total of 54 pairs and ratios were identified. No clear tendency of correlation is found in a brief view of the ratios. The cumulative distribution function (CDF) of the data is plotted in Fig. 1 and compared with the random-switching CDF obtained by assuming that the two modes are independent gamma distributions with the best fitted parameters $(k_n, k_a, \tau_n, \tau_a) = (0.75, 0.84, 154, 31.5)$, depicted by the smooth curve.

In order to test if the distribution of real ratios is consistent with the random-switching ratio distribution, we perform Kolmogorov-Smirnov (KS) test. While considering the uncertainty in the parameters $(k_n, k_a, \tau_n, \tau_a)$, we set up 54 grid points spanning the 95% confidence interval of the four parameters, and each grid point yields a random-switching ratio distribution. We then calculate the probability in KS test for each pair of the real data and a grid point. Fig. 2 presents the CDF of the probability value of KS test. The results show that the probability is larger than 5% (the highest up to 95%) for nearly 53% of the grid points, which means the distribution of real ratio data is consistent with random-switching distribution in these cases at 5% significance level. This fraction increase to 70% at 1% significance level. The small fraction of inconsistency may result from the uncertainty in the measured timescales (note that the smallest integration time to obtain a pulse profile is 1 minute, see Chen et al. 2011).

3. Discussion

The above results show that there is no correlation between the timescales of normal and abnormal modes. The duration of an abnormal mode is independent to the duration of the preceding normal mode.

We also investigated another problem: is it possible to constrain the intrinsic distribution of mode timescales by using non-continuous observations? One may concern this...

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Figure 1. Stepwise curve: Cumulative distribution function (CDF) of the ratio $t_n/t_a$, where $t_n$ and $t_a$ are the durations of a normal mode and the succeeding abnormal mode, respectively. Smooth curve: the CDF assuming that the two modes are independent gamma distributions with the best fitted parameters $(k_n, k_a, \tau_n, \tau_a) = (0.75, 0.84, 154, 31.5)$
Figure 2. Cumulative distribution function of the probability $p$ in KS test for 54k grid points. The two dashed lines represent for $p = 1\%$ and $p = 5\%$.

when there is no long and continuous observations but a number of historical data of separated observations. Based on the 90 separated observations with XAO 25m telescope, mostly 2-hour long, we use Monte Carlo method to simulate the mode timescales in the given observational time windows, and then compare with the observed timescales to constrain the parameters of gamma distributions. However, the constrained region in parameter space is much wider than that determined with continuous observations. Therefore, it is important that the observational time intervals should be much larger than the typical timescale of modes.

Acknowledgement

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Curvature radiation in rotating pulsar magnetosphere

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Abstract. We investigate the curvature radiation from relativistic particles streaming along magnetic field lines and co-rotating with a pulsar. The co-rotation affects the trajectories of the particles and hence the emission properties, especially the polarization. For three density models in the form of core, cone and patches, we calculate the polarized emission at a given height and also the integrated emission for the whole open field line region, and try to explain the generation of circular polarization.

Keywords. polarization, radiation mechanisms: nonthermal, pulsars: general

1. Introduction

The observed pulsar radio emission are generally highly linearly polarized, and have significant circular polarization (e.g., Lyne & Manchester 1988; Han et al. 1998; Rankin & Ramachandran 2003). Various radio emission mechanisms are suggested to explain polarization profiles (e.g., Beskin et al. 1988; Xu et al. 2000; Gangadhara 2010). Curvature radiation serves as one of the most possible emission mechanisms for pulsar radio emission and has been investigated extensively for the coherent emission process, pulsar luminosity, emission spectrum and the polarization features (Buschauer & Benford 1976; Benford & Buschauer 1977; Ochelkov & Usov 1980; Gil & Snakowski 1990; Gangadhara 2010).

Most previous studies on pulsar curvature radiation ignore the effects of rotation. Relativistic particles in pulsar magnetosphere have co-rotation velocity additional to the streaming velocity along the curved magnetic field lines, which affects the radiation properties. For example, the rotation causes a phase lag between the centers of the position angle curve and the profile (Blaskiewicz et al. 1991). The rotation influences the intensities of the leading and trailing components of the profile (Thomas & Gangadhara 2007; Dyks et al. 2010).

We depicted the most detailed scenery for pulsar curvature radiation (Wang et al. 2012), especially for the polarized emission features. The emission from particles on the nearby field lines within the $1/\gamma$ emission cone is considered for a given phase and height. The polarization profiles from a given height and the whole open field line region are calculated for three possible density distributions in the form of core, cone and patches.

2. Pulsar Curvature Radiation

For our calculation, we assume co-rotating relativistic particles in the inclined dipole magnetosphere distributed in the form of core, cone and patch, which radiate in curvature radiation mechanism.

In the co-rotating frame, one relativistic particle or bunch is streaming along a open
magnetic field line with velocity $v'$ and acceleration $a'$. The particle trajectory along the magnetic field line is approximated to be circular path in our calculation, because the radiation emitted by an extremely relativistic particle is equivalent to that from a particle moving on an appropriate circular path. The particle also experiences rotation with velocity $v_r$. In the lab frame, the total velocity, $\mathbf{v}$, should be the addition of $\mathbf{v}'$ with $\mathbf{v}_r$ by Lorentz transformation and the total acceleration is the derivative of $\mathbf{v}$. As the radiation of a relativistic particle is beamed in its velocity direction, $\hat{\mathbf{v}}$. The emission location can be determined by requiring the alignment between the wave vector unity $\mathbf{n}$ and $\hat{\mathbf{v}}$. Knowing the velocity, acceleration and emission location of the relativistic particle, we can directly calculate its curvature radiation fields.

The curvature radiation at a given height and rotation phase has the contributions from particles streaming along many nearby field lines around the central tangential point, forming the emission cone of $1/\gamma$. The total intensity distributes elliptically around the central maximum. The linear polarization has almost the same pattern as total intensity but with a smaller magnitude. The circular polarization has two antisymmetrical lobes with + and − signs corresponding to the left and right hands. Such a polarization pattern of an emission cone is distorted by the additional rotation, more seriously for emission from a larger height.

The observed Stokes parameters of each rotation phase and height are the integration of the entire beam patterns. The particles within the $1/\gamma$ emission cone may have some kind of density distribution across the field lines. The density gradient across the pattern may result in the net circular polarization. The emission profile is calculated by the integration of the polarized emission at each rotation phase. Due to rotation, the “S” shaped position angle curve is shifted towards a later phase, while the intensity curve to an earlier phase compared to those without rotation. Different density models show different polarization behavior. The particles distributed in density core result in net circular polarization with a single sign for all rotation phases. The emission from a density cone has two components at a large height with sign reversals for circular polarization, but at a lower height they merged to one component with a single sign of circular polarization. For emission from particles in a given density patch, different cuts of a line of sight will cause different profiles. Even when the cuts of a line of sight is fixed, the polarization profiles will be different for various emission heights.

For a given line of sight, the received emission comes from the tangential points of a range of field lines in a range of heights, and have to be integrated to give the total

![Figure 1](image-url)
observed emission for a rotation phase. For the core density model, the circular polarization of the integrated profile has only one single sign (Fig. 1a). The integrated profile from particles in cone density model has insignificant circular polarization due to depolarization (Fig. 1b), and the integrated emission profile in the open field line region from particles in density patches shows the reversal of circular polarization (Fig. 1c).

3. Conclusion

We calculated the curvature radiation of particles in the rotating pulsar magnetosphere, and got the following conclusions:

(a) Rotation not only shifts the PA curves along the rotation phase, but also causes an offset, both of which are the first-order functions of the emission height. Their influences on pulsar geometry determination follows the second order functions.

(b) Rotation distorts the patterns for the $1/\gamma$ emission cone more seriously from larger height and/or smaller impact angle. The density gradients across the patterns will result in the net circular polarization.

(c) For the patch density model, the sense change of circular polarization depends on the impact angle of the sight line. The polarization profiles for a fixed impact angle also vary with emission heights.

(d) The emission from the central peaked density core will usually have significant circular polarization of only one hand. The emission from a density cone has two components at a large height with sign reversals for circular polarization, but at a lower height there is only one component with a single sign of circular polarization.

Our calculations can explain some pulsar polarized emission, but our results can not explain all observational facts. In our model, we did not consider the detailed coherence of the emission and the possible propagation effects. The actual energy and density distributions of particles in the magnetosphere are not clear yet. Furthermore, other emission mechanisms may also work for the observed emission.

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References

Pulsed $\gamma$-ray emission from magnetar 1E 2259+586


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Abstract. Anomalous X-ray pulsars (AXPs) are thought to be magnetars which are young isolated neutron stars with extremely strong magnetic fields of $> 10^{14}$ Gauss. Their tremendous magnetic fields inferred from the spin parameters provide a huge energy reservoir to power the observed X-ray emission. High-energy emission above 0.3 MeV has never been detected despite intensive search. Here, we present the possible Fermi Large Area Telescope (LAT) detection of $\gamma$-ray pulsations above 200 MeV from the AXP, 1E 2259+586, which puts the current theoretical models of $\gamma$-ray emission mechanisms of magnetars into challenge. We speculate that the high-energy $\gamma$-rays originate from the outer magnetosphere of the magnetar.

Keywords. gamma rays: observations, (stars:) pulsars: individual (1E 2259+586), radiation mechanisms: nonthermal

1. Introduction

Neutron stars are now known to have many different manifestations besides rotation-powered and accretion-powered pulsars. While pulsars typically have a surface magnetic field of $\sim 10^{12}$ G, it has been suggested that neutron stars can possess magnetic fields with a strength as high as $\sim 10^{15}$ G (Duncan & Thompson 1992). These highly magnetized neutron stars are called magnetars. The existence of magnetars provides a unique laboratory for exploring the physics of compact objects in the presence of a ultra-strong magnetic field. Based on current observations and theories, the emission from magnetars mainly emerges in X-ray energy bands; their broad band spectral shapes can be well described by a blackbody component (with a hard tail probably due to Compton scattering) below 10 keV, which is likely from the magnetar surface, plus a non-thermal component dominating above 10 keV, which is from the magnetosphere (Thompson et al. 2002). On the basis of theoretical models of high-energy emission from magnetars, it is not expected to detect emission above $\sim 1$ MeV (Thompson et al. 1995).

Although Castro et al. (Castro et al. 2012) have report the $\gamma$-ray emission from CTB 109, which is also well-known for hosting an AXP 1E 2259+586, they concluded that 1E 2259+586 is not likely to be contributing the observed $\gamma$-ray flux. We have done a detail timing analysis based on the timing ephemeris reported in (Icdem et al. 2012), a 5-sigma $\gamma$-ray pulsation from 1E 2259+586 was found. The possible detection of the $\gamma$-ray pulsation suggest that 1E 2259+586 could also contribute part of the $\gamma$-ray flux.
2. Data analysis

For the spectral analysis, we used the LAT data between 2008 August 04 and 2011 November 09 (3.5 years of data). To reduce and analyze the data, the Fermi Science Tools v9r23p1 package, available from the Fermi Science Support Center, was used. We used Pass 7 data and selected events in the Source class (i.e. event class 2) only. In addition, we excluded the events with zenith angles larger than 100° to greatly reduce the contamination by Earth albedo gamma-rays. The instrumental response functions (IRFs) P7SOURCE V6 were adopted throughout the study. Figure 1 shows the binned energy spectrum of CTB 109/1E 2259+586. As 1E 2259+586 is known to have frequent glitches, sudden increases in its spin frequency, we only used data taken after the last glitch seen on 2009 February 18 to search for γ-ray pulsation. By the timing ephemeris report by Icdem et al. (2012), the period after the microglitch 2 is found to be 6.979060682 s. With the aid of the Fermi plug-in for TEMPO2, we assigned a spin phase for each γ-ray photon with energy greater than 200 MeV that fell within 0.6° from the AXP position. Pulsed γ-ray emission was found after 120 days since the latest microglitch reported. The folded pulse profile for epoch 2 only is shown in Figure 2 with a 5-sigma pulsation significance using H-test; the 120 days delay of the γ-ray pulsation could be explained by the decrease of the soft X-ray flux during the above period as the soft X-ray photon would cause photon photon pair creation which eventually prevents those γ-ray photons to escape from the magnetar. Swift X-ray observation reveal that the soft X-ray flux on 1E 2259+586 during the above period is two times smaller than other epoch. From the folded lightcurve in epoch 2 we can estimate the pulsed fraction to be ~ 30%. Previous searches on magnetars by Abdo et al. (2010) show no conclusive evidence using 17 months of LAT data. The non-detection on 1E 2259+586 can be explained as Abdo et al. only include LAT photons up to 01 January 2010 (~55200 MJD); which covers only part of the epoch 2, preventing detection of pulsed γ-rays from 1E 2259+586.
3. Discussion

If the detection of the pulsed $\gamma$-ray from 1E 2259+586 is genuine, it makes 1E 2259+586 as the first magnetar with GeV $\gamma$-ray emission. It also demonstrates that magnetars are capable of emitting GeV $\gamma$-rays similar to canonical $\gamma$-ray pulsars which are powered by the rotational energy. It was indeed predicted more than a decade ago that GeV $\gamma$-rays can originate from the outer magnetosphere of a magnetar (Cheng et al. 2001). However, the acceleration mechanism of the observed pulsed $\gamma$-ray radiations is probably different from the existing model. First, the observed pulsed $\gamma$-ray must be produced far from the magnetar surface to avoid absorption through the one photon pair-creation process, and/or the two photon pair-creation process. For a magnetar, it is likely that the observed pulsed $\gamma$-rays are produced at $>1000$ km above the stellar surface. Second, the luminosity of the observed pulsed $\gamma$-ray, $L_\gamma \sim 10^{34}$ erg s$^{-1}$ (assuming isotropic emissions), is well above its spin down power, $L_{sd} \sim 10^{31}$ erg s$^{-1}$, suggesting that unlike canonical pulsars, the emission process is not powered by its rotational energy loss. Finally, the observational results obtained by X-ray and $\gamma$-ray instruments have suggested that the high-energy emissions of magnetars do not extend beyond several hundred keV (Kuiper et al. 2004; den Hartog et al. 2008; Enoto et al. 2010; Kuiper et al. 2012; Abdo et al. 2010). This suggest that the pulsed X-rays and $\gamma$-rays are produced by different mechanisms.

References

Constraints on the standard model extension with binary pulsars

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Abstract. Under the standard model extension (SME) framework, Lorentz invariance is tested in five binary pulsars: PSR J0737-3039, PSR B1534+12, PSR J1756-2251, PSR B1913+16 and PSR B2127+11C. By analyzing the advance of periastron, we obtain the constraints on a dimensionless combination of SME parameters that is sensitive to timing observations. The results imply no evidence for the break of Lorentz invariance at $10^{-10}$ level, one order of magnitude larger than previous estimation.

Keywords. gravitation, relativity, pulsars: PSR 0737-3039, PSR B1534+12, PSR J1756-2251, PSR B1913+16, PSR B2127+11C

1. Introduction

Unification of general relativity (GR) and quantum mechanics is a grand challenge in the fundamental physics. Some candidates of a self-consistent quantum theory of gravity emerge from tiny violations of Lorentz symmetry (Kostelecký 2005; Mattingly 2005). To describe observable effects of the violations, effective field theories could be a theoretical framework for tests.

The standard model extension (SME) is one of those effective theories. It includes the Lagrange densities for GR and the standard model for particle physics and allows possible breaking of Lorentz symmetry (Bailey & Kostelecký 2006). The SME parameters $\bar{s}^{\mu\nu}$ control the leading signals of Lorentz violation in the gravitational experiments in the case of the pure-gravity sector of the minimal SME. By analyzing archival lunar laser ranging data, Battat et al. (2007) constrain these dimensionless parameters at the range from $10^{-11}$ to $10^{-6}$, which means no evidence for Lorentz violation at the same level.

However, tighter constraints on $\bar{s}^{\mu\nu}$ would be hard to obtain in the solar system because the gravitational field is weak there. Thus, for this purpose, binary pulsars provide a good opportunity. Because of their stronger gravitational fields, for example the relativistic periastron advance in the double pulsars could exceed the corresponding value for Mercury by a factor of $\sim 10^5$, these systems are taken as an ideal and clean test-bed for testing GR, alternative relativistic theories of gravity and modified gravity, such as the works by Bell et al. (1996), Damour & Esposito-Farèse (1996), Kramer et al. (2006), Deng (2009) and Deng (2011).

Motivated by this advantage of binary pulsars, we will try to test Lorentz invariance under the SME framework with five binary pulsars: PSR J0737-3039, PSR B1534+12, PSR J1756-2251, PSR B1913+16 and PSR B2127+11C. In Section 2, the orbital dynamics of double pulsars in the SME will be briefed. Observational data will be used to constrain the SME parameters in Section 3. The conclusions will be presented in Section 4.
2. Orbital dynamics of double pulsars in SME

When the pure-gravity sector of the minimal SME is considered, it will cause secular evolutions of the orbits of double pulsars. Since timing observations of double pulsars could obtain its value very precisely, the periastron advance plays a much more important role in constraining $\delta \mu^\nu$ and, with widely used notations in celestial mechanics, it reads (Bailey & Kostelecký 2006)

$$\left\langle \frac{d\omega}{dt} \right\rangle_{\text{SME}} = -\frac{n}{\tan i(1-e^2)^{1/2}} \left[ \frac{\varepsilon}{c^2} s_{kP} \sin \omega + \frac{(e^2-\varepsilon)}{e^2} s_{kQ} \cos \omega - \frac{\delta m}{M} 2nae\bar{s}_k \cos \omega \right]$$

$$-n \left[ \frac{(e^2-2\varepsilon)}{2e^4} (\bar{s}_{PP} - \bar{s}_{QQ}) + \frac{\delta m}{M} 2na(e^2-\varepsilon) \right],$$

(2.1)

where $M = m_1 + m_2$, $\delta m = m_2 - m_1$ ($m_2 > m_1$) and $\varepsilon = 1-(1-e^2)^{1/2}$. In this expression, the coefficients $\bar{s}$ and $\bar{s}_k$, for Lorentz violation with subscripts $P$, $Q$ and $k$ are projections of $\delta \mu^\nu$ along the unit vectors $P$, $Q$ and $k$. The unit vector $k$ is perpendicular to the orbital plane of the binary pulsars, $P$ points from the focus to the periastron, and $Q = k \times P$. By definitions (Bailey & Kostelecký 2006), $s_k \equiv s^{(j)}k^j$, $s_Q \equiv s^{(j)}Q^j$, $s_{kP} \equiv s^{(j)}k^jP^j$, $s_{kQ} \equiv s^{(j)}k^jQ^j$, $s_{PP} \equiv s^{(j)}P^jP^j$ and $s_{QQ} \equiv s^{(j)}Q^jQ^j$. However, according to Eq. (2.1), it is easy to see that the measurement of $\bar{\omega}$ is sensitive to a combination of $\bar{s}_k$ instead of its individual components. Bailey & Kostelecký (2006) define the combination as

$$\bar{s}_k \equiv s_{kP} \sin \omega + (1-e^2)^{1/2} s_{kQ} \cos \omega - \frac{\delta m}{M} 2nae\bar{s}_k \cos \omega$$

$$+ \tan i(1-e^2)^{1/2}(e^2-2\varepsilon) \left( \bar{s}_{PP} - \bar{s}_{QQ} \right) + \frac{m}{M} 2na \tan i \frac{(e^2-\varepsilon)}{e} \bar{s}_Q,$$

(2.2)

and crudely estimate its value at the level of $10^{-11}$.

Together with the contribution from GR, the total secular periastron advance of a double pulsars system is

$$\dot{\omega} = 3 \left( \frac{P_\circ}{2\pi} \right)^{-5/3} \left( \frac{GM_{\odot}}{c^3} \right)^{2/3} (1-e^2)^{-1} - \frac{n\varepsilon}{\tan i(1-e^2)^{1/2}e^2} \bar{s}_\omega$$

$$= 3 \left( \frac{P_\circ}{2\pi} \right)^{-5/3} T_{\odot}^{2/3} \left( \frac{M}{M_{\odot}} \right)^{2/3} (1-e^2)^{-1} - \frac{2\pi\varepsilon s}{P_\circ(1-e^2)^{1/2}c^2(1-s^2)^{1/2}} \bar{s}_\omega,$$

(2.3)

where $T_\odot \equiv GM_{\odot}/c^3 = 4.925490947$ μs and

$$s = x \left( \frac{P_\circ}{2\pi} \right)^{-2/3} T_{\odot}^{-1/3} M^{2/3} m_2^{-1}.$$

(2.4)

The quantity $x$ in Eq. (2.4) is the projected semi-major axis, which is usually given by the timing observations, while, in some cases, $s$ could be measured directly so that there is no necessity to evaluate it from this equation. In this work, Eq. (2.3) will be taken to find the constraints on $\bar{s}_\omega$ with timing measurements of double pulsars.

3. Observational constraints

Long-term timing observations can determine the geometrical and physical parameters of binary pulsars very well. Among them, PSR J0737-3039 (Kramer et al. 2006), PSR B1534+12 (Stairs et al. 2002), PSR J1756-2251 (Faulkner et al. 2005), PSR B1913+16 (Weisberg et al. 2010) and PSR B2127+11C (Jacoby et al. 2006) are good samples for gravitational tests. Some of their timing parameters are listed in the Table 1. In terms
Table 1. Timing Parameters of the Double Pulsars.

<table>
<thead>
<tr>
<th>PSR</th>
<th>$P_b$ (d)</th>
<th>$M$ ($M_\odot$)</th>
<th>$e$</th>
<th>$s$</th>
<th>$\dot{\omega}$ ($\degree$ yr$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0737-3039</td>
<td>0.10225156248</td>
<td>2.58708</td>
<td>0.0877775</td>
<td>0.99974</td>
<td>16.89947(68)</td>
<td>Kramer et al. (2006)</td>
</tr>
<tr>
<td>B1534+12</td>
<td>0.420737299122</td>
<td>2.678428</td>
<td>0.2736775</td>
<td>0.975</td>
<td>1.755789(9)</td>
<td>Stairs et al. (2002)</td>
</tr>
<tr>
<td>J1756-2251</td>
<td>0.319633898</td>
<td>2.574</td>
<td>0.180567</td>
<td>0.961</td>
<td>$2.585(2)$</td>
<td>Faulkner et al. (2005)</td>
</tr>
<tr>
<td>B1913+16</td>
<td>0.322997448911</td>
<td>2.828378</td>
<td>0.6171334</td>
<td>0.73650$^a$</td>
<td>4.226598(5)</td>
<td>Weisberg et al. (2010)</td>
</tr>
<tr>
<td>B2127+11C</td>
<td>0.33528204828</td>
<td>2.71279</td>
<td>0.681395</td>
<td>0.76762$^a$</td>
<td>4.4644(1)</td>
<td>Jacoby et al. (2006)</td>
</tr>
</tbody>
</table>

$^a$Derived value according to Eq. (2.4).

Table 2. Values of $\bar{s}_\omega$.

<table>
<thead>
<tr>
<th>Group I</th>
<th>$\bar{s}_\omega \times 10^{-10}$</th>
<th>Group II</th>
<th>$\bar{s}_\omega \times 10^{-10}$</th>
<th>Predicted sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bailey &amp; Kostelecký (2006)</td>
<td>$(-1.24 \pm 0.54) \times 10^{-10}$</td>
<td>$(-1.42 \pm 0.75) \times 10^{-10}$</td>
<td>$10^{-11}$</td>
<td></td>
</tr>
</tbody>
</table>

of the estimated uncertainties given in parentheses after $\dot{\omega}$, the data pool is divided into two groups: Group I, all the double pulsars are taken; and Group II, including PSR B1913+16, PSR B1534+12 and PSR B2127+11C, which have the smallest uncertainties.

By weighted least square method, the parameter $\bar{s}_\omega$ is estimated (see Table 2). The estimation made by Group I is $\bar{s}_\omega = (-1.24 \pm 0.54) \times 10^{-10}$ and Group II gives $\bar{s}_\omega = (-1.42 \pm 0.75) \times 10^{-10}$. For comparison, Bailey & Kostelecký (2006) propose the attainable experimental sensitivity of $\bar{s}_\omega$ is $10^{-11}$, which is 10 times less than the results we obtain.

4. Conclusions

In this work, we test Lorentz violation with five binary pulsars under the framework of standard model extension. It finds that $\bar{s}_\omega$, which is a dimensionless combination of SME parameters, is at the order of $10^{-10}$, whether all five systems are taken or top three systems with the smallest estimated uncertainties of periastron advances are used. This value, one order of magnitude greater than the estimation by Bailey & Kostelecký (2006), implies no evidence for the break of Lorentz invariance at $10^{-10}$ level.

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Modeling pulsar time noise with long term decay modulated by short term oscillations of the magnetic fields of neutron stars

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Abstract. We model the evolution of the magnetic fields of neutron stars as consisting of a long term power-law decay modulated by short term small amplitude oscillations. Our model predictions on the timing noise of neutron stars agree well with the observed statistical properties and correlations of normal radio pulsars. For individual pulsars our model can effectively reduce their timing residuals, thus offering the potential of more sensitive detections of gravitational waves with pulsar timing arrays. Finally our model can also re-produce their observed correlation and oscillations of second derivative of frequency, as well as the ""slow glitch"" phenomenon.
VLBI astrometry of two millisecond pulsars

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Abstract. We present astrometric results on two millisecond pulsars, PSR B1257+12 and PSR J1022+1001, as carried out through VLBI. For PSR B1257+12, a model-independent distance of \(710^{+43}_{-38}\) pc and proper motion of \((\mu_\alpha = 46.44 \pm 0.08 \text{ mas/yr}, \mu_\delta = -84.87 \pm 0.32 \text{ mas/yr})\) were obtained from 5 epochs of VLBA and 4 epochs of EVN observations, spanning about 2 years. The two dimensional proper motion of PSR J1022+1001 \((\mu_\alpha \sim -10.13 \text{ mas/yr}, \mu_\delta \sim 16.89 \text{ mas/yr})\) was also estimated, using 3 epochs of EVN observations. Based on our results, the X-ray efficiency of PSR B1257+12 should be in the same range as other millisecond pulsars, and not as low as previously thought.

Keywords. (stars:) pulsars: general

1. Introduction

The distance and proper motion are fundamental and important pulsar parameters. A model-independent distance and proper motion measurement is especially important for millisecond pulsars (MSPs). Firstly, MSPs are old enough to leave the Galactic disk. Model-independent pulsar distance measurements indicate that the TC93 (Taylor & Cordes 1993) or NE2001 (Cordes & Lazio 2002) Galactic electron density distribution model underestimates the distances for high-latitude pulsars (Chatterjee et al. 2009). Secondly, the distance and proper motion of a pulsar are also important parameters in the pulsar timing observation. In the Shklovskii effect, for example, a transverse component of this pulsar velocity gives rise to an appreciable increase in the apparent period even if the pulsar is not slowing down (Shklovskii 1970). For MSPs, \(P_{\text{Shk}} \sim 10^{-19} \text{ s/s}\), comparable to their observed first order period derivative. Furthermore, MSPs have more parameters to fit in timing observations, as most of them have companions. If the distance and proper motion have been obtained independently, it will be helpful for the other parameters fitting.

High precision VLBI astrometry offers a powerful way to directly measure the parallaxes and proper motions of pulsars. With the steady progress of VLBI observation, correlation and data processing techniques, VLBI astrometry of some pulsars has been accomplished successfully (Campbell et al. 1996; Fomalont et al. 1999; Brisken et al. 2002; Chatterjee et al. 2009; Deller et al. 2009).

Here, we report the progress of our astrometry project on two MSPs, PSR B1257+12 and PSR J1022+1001, with the VLBA and EVN. PSR B1257+12 is the first extrasolar planetary system discovered. It has been confirmed that PSR B1257+12 has three planets in approximately co-planar orbits (Wolszczan et al. 2000). PSR J1022+1001 is an intermediate mass binary pulsar accompanied by a 0.9 \(M_\odot\) white dwarf. It lies
Table 1. The distance and proper motion of PSR B1257+12 and PSR J1022+1001

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Distance (pc)</th>
<th>Proper motion (mas/yr)</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1257+12</td>
<td>~ 620</td>
<td></td>
<td>TC93</td>
<td>Taylor &amp; Cordes (1993)</td>
</tr>
<tr>
<td></td>
<td>800 ± 200</td>
<td>$\mu_\alpha = 46.4 \pm 0.1$</td>
<td>Timing</td>
<td>Wolszczan et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>~ 450</td>
<td>$\mu_\alpha = 45.5 \pm 0.4$</td>
<td>Timing</td>
<td>Konacki &amp; Wolszczan (2003)</td>
</tr>
<tr>
<td></td>
<td>660$^{+140}_{-140}$</td>
<td>$\mu_\alpha = 46.44 \pm 0.08$</td>
<td>VLBI</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>710$^{+43}_{-38}$</td>
<td>$\mu_\delta = -84.87 \pm 0.32$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1022+1001</td>
<td>~ 600</td>
<td>$\mu_\alpha = -17 \pm 2$</td>
<td>TC93</td>
<td>Taylor &amp; Cordes (1993)</td>
</tr>
<tr>
<td></td>
<td>~ 440</td>
<td>$\mu_\alpha \sim -10.13$</td>
<td>Timing</td>
<td>Kramer et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>300$^{+100}_{-60}$</td>
<td>$\mu_\delta \sim 16.89$</td>
<td>Timing</td>
<td>Hotan et al. (2004)</td>
</tr>
</tbody>
</table>

near the ecliptic plane, so that only the component of proper motion along the ecliptic longitude can be accurately measured with pulsar timing method (Kramer et al. 1999). For these two pulsars, the astrometry results obtained by various methods are by now very different (see Table 1). So, it is meaningful to perform VLBI astrometry on these pulsars and further study their related astrophysics.

2. Observations and data reduction

The flux density of PSR B1257+12 and PSR J1022+1001 is about 2 and 3 mJy at 1400 MHz, respectively. The corresponding observing wavelength of VLBA and EVN is 21 cm and 18 cm, respectively. Including 5 epochs of VLBA observation and 4 epochs of EVN observation, there are 9 epochs of VLBI observations of PSR B1257+12 spanning 2 years. In the VLBA observations of PSR B1257+12, two calibrators, J1300+1206 and J1300+141A, located on opposite sides of PSR B1257+12 in RA direction with the separation of 0.58° and 1.61°, were selected as phase reference sources. In the EVN observations of PSR B1257+12, only J1300+141A was selected as the phase reference source. One phase reference source at 2.96° away was chosen in PSR J1022+1001 observations with the EVN. Only 3 of 5 epochs EVN observations of PSR J1022+1001 were successful. The VLBA and EVN data were correlated with NRAO-DiFX and Bonn-DiFX software correlators under the pulsar binning mode, respectively. The data was processed with AIPS following the normal data reduction steps of phase reference observations.

3. Results and Discussion

Firstly, the astrometric parameters of PSR B1257+12 are fitted with the standard weighted least squares method with 5 degrees of freedom that astrometry measurements usually use. But, there are some systematic offset in the DEC direction between VLBA results and EVN results. To overcome this, one more parameter $\Delta\delta_{(\text{EVN-VLBA})}$ is added to the new data fitting. The reduced $\chi^2$ of the new fitting is 0.67 with a fitted systematic
offset $\Delta d_{(\text{EVN-VLBA})}$ of 1.22 mas. The parallax fitted is $1.41 \pm 0.08$ mas, which corresponds to a distance $710^{+13}_{-38}$ pc. The corresponding proper motion in RA and DEC direction is $46.44 \pm 0.08$ and $-84.87 \pm 0.32$ mas/yr. The covariance between parallax ($\pi$) and proper motion ($\mu_\alpha$, $\mu_\delta$) is -0.0239 and -0.0897, respectively. For comparison our astrometric measurement results are listed in Table 1.

Some debris left over from the planet formation may cause PSR B1257+12 to be of low apparent X-ray efficiency. It is hard to conclude whether this pulsar is low apparent X-ray efficient or not because of distance uncertainties (Pavlov et al. 2007). According to the X-ray measurement results from Pavlov et al. (2007) and our new distance result, for the 90% confidence lower boundary of the distance 649 pc, the X-ray efficiency of this pulsar is $9.63 \times 10^{-5}$. The best fitted distance 710 pc gives an X-ray efficiency of $1.68 \times 10^{-4}$. So, our new VLBI result indicates that the X-ray efficiency of PSR B1257+12 should still be in the same range ($\sim 10^{-4} - 10^{-2.5}$) as other MSPs.

As we only have 3 epochs of successful observations of PSR J1022+1001 with the EVN, it is impossible to fit both the distance and proper motion of this pulsar. Using the distance ($\sim 300$ pc) of PSR J1022+1001 obtained with timing method (Hotan et al. 2004), the two dimensional proper motions $\mu_\alpha = -10.13$ mas/yr, $\mu_\delta = 16.89$ mas/yr, as estimated with these 3 epochs EVN measurements.

We plan an astrometry project of more MSPs, including PSR J1022+1001, whose model-independent distance has not been obtained in our present work.

**Acknowledgements**

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**References**


On the origin of the low-frequency QPO in GRS 1915+105 $\rho$ state

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Abstract. We performed a phase-resolved timing analysis of GRS 1915+105 in its $\rho$ state and identify detailed $\rho$ cycle evolution of frequency, amplitude and coherence of the low-frequency quasi-periodic oscillation (LFQPO). We combined our timing results with the spectral study by Neilsen et al. (2011) to do an elaborate contrast analysis. The results are naturally explained by tying the LFQPO to the corona.

Keywords. accretion, accretion disks, oscillations, GRS 1915+105

1. Introduction

GRS 1915+105 is a binary system which was discovered by the WATCH instrument on board GRANAT in 1992 (Castro-Tirado et al. 1992). It is located in our galaxy at an estimated distance of about 11 kpc (e.g., Fender et al. 1999; Zdziarski et al. 2005), containing a spinning black hole (Zhang et al. 1997; McClintock et al. 2006) with mass about $14\pm 4 \, M_\odot$ and a K-M III giant star with mass $0.8\pm 0.5 \, M_\odot$ as the donor (Harlaftis & Greiner 2004; Greiner et al. 2001). As the first found microquasar, GRS 1915+105 produces superluminal radio jets (Mirabel & Rodríguez 1994; Fender et al. 1999). The count rate and color characteristics are extremely complex, and the light curves of the source are usually classified into 12 variability classes (Belloni et al. 2000).

Research on GRS 1915+105 has revealed that its LFQPO frequency is positively correlated with the flux of the thermal and power law components and total intensity (e.g., Chen et al. 1997; Markwardt et al. 1999; Muno et al. 1999, 2001; Trudolyubov et al. 1999; Tomskick & Kaaret 2001). The LFQPO amplitude is inversely correlated with the source flux or LFQPO frequency (e.g., Muno et al. 1999; Reig et al. 2000). As the LFQPO frequency increases, the temperature of the inner accretion disk increases and the radius of the inner accretion disk decreases (e.g., Rodriguez et al. 2002a). The LFQPO amplitude increases with photon energy and it turns over in high energy bands in some cases (e.g., Tomskick & Kaaret 2001; Rodriguez et al. 2002b, 2004; Zdziarski et al. 2005). As the centroid frequency of LFQPO increases, the correlation between LFQPO frequency and photon energy evolves from negative to positive (Qu et al. 2010). In addition, three more combined patterns of negative to positive correlation were discovered (Yan et al. 2012).

Although the results mentioned above enable a good understanding of LFQPO, we are puzzled by the ambiguous fact that LFQPO is correlated with both corona/jet and accretion disk. Neilsen et al. (2011; hereafter NRL11) investigated the physical changes and the LFQPO evolution of the $\rho$ variability in GRS 1915+105 through a phase-resolved spectral and timing analysis. In order to reveal more clues about the origin of the LFQPO and more details about evolution of the $\rho$ cycle, we follow up in this work with a detailed contrast analysis between the results of spectral and timing analyses.
2. Data reduction and results

Using a method similar to that of NRL11, we do a phase-resolved timing analysis for 60405-01-02-00, the same RXTE observation of GRS 1915+105 analyzed by NRL11.

For each 0.02 phase interval the power density spectrum (PDS) is computed in the 2.0 – 37.8 keV band and the results are shown in Fig. 1. The phase-folded PCA ρ class lightcurve (Fig. 1a) and the 0.5 – 10 Hz amplitude shape (Fig. 1b) are similar to those of NRL11. Based on the behavior of the LFQPO amplitude (Fig. 1d), the cycle phase is divided into six intervals (I: 0.02 – 0.12, II: 0.12 – 0.26, III: 0.26 – 0.4, IV: 0.4 – 0.74, V: 0.74 – 0.92, and VI: 0.92 – 0.02). In the interval I, there is no obvious LFQPO. In intervals II and VI, the LFQPO amplitude is positively correlated with the LFQPO frequency. While in intervals III, IV and V, the LFQPO amplitude is negatively correlated with the LFQPO frequency. As phase increases, the LFQPO frequency decreases (II and III), flattens (IV) and then increases again (V). It is very interesting that LFQPO frequency remains constant in the interval IV, and drops at ϕ = 0.92 (Fig. 1c). As phase increases, the coherence of LFQPO increases rapidly (II), decreases quickly (III) and continues to decrease very slightly (IV, V and VI) (Fig. 1e).

3. Implications

In the ρ state, NRL11 showed that the energy spectrum has at least two components: the disk emission and the corona emission.

As phase increases, the LFQPO frequency decreases (II and III), flattens (IV) and then increases again (V) (Fig. 1c), while accretion disk radius increases continuously over the phase range 0.1 – 0.9, which covers intervals II, III, IV, and V (Fig. 7 in NRL11), suggesting that the LFQPO seems to be irrelevant to the accretion disk.

![Figure 1](image-url) Figure 1. (a) The phase-folded PCA ρ class lightcurve in 2.0 – 37.8 keV band. (b) 0.5 – 10 Hz rms amplitude, (c) LFQPO frequency. (d) LFQPO amplitude, and (e) LFQPO coherence, as a function of ρ cycle phase.
In the interval IV, which is covered by the slow rise of NRL11, both the LFQPO frequency and power-law index are relatively steady while the radius of the inner disk increases significantly (Fig. 1; Fig. 7 in NRL11). The fact that the LFQPO frequency and the power-law index remain relatively stable coincidentally indicates a possible correlation between the LFQPO and the corona.

There is no obvious LFQPO in the interval I, during which there is a hard pulse called by NRL11. NRL11 argued that some material collides with the hot corona after it has been ejected from the inner disk due to disk instability during the hard pulse phase. Based on the presumption that LFQPO is produced in the corona, the absence of LFQPO may be caused by the violent disturbance in the corona owing to the collision.

The LFQPO frequency decreases smoothly during intervals II and III, which cover NRL11’s phase of the hard X-ray tail during which a short-lived jet is said to be produced. Then the jet seems independent with the LFQPO considering that it has no influence on the LFQPO frequency based on the smooth evolution of the LFQPO frequency.

The LFQPO frequency drops at $\phi = 0.92$ (Fig. 1c). NRL11 argued that the disk becomes unstable and the inner disk radius decreases rapidly after phase 0.9 due to radiation pressure. The drop in the LFQPO frequency might be another signal which indicates that the corona has been changed significantly.

In summary, it shows that the LFQPO likely originate from the corona.

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Rotation Measure variations for millisecond pulsars

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Abstract. As part of the Parkes Pulsar Timing Array (PPTA) project, frequent observations of 20 millisecond pulsars are made using the Parkes 64-m radio telescope. Variations in the mean position angle of the 20 millisecond pulsars can be studied by the PPTA data being recorded in full-polarization mode. We briefly discuss these results.

Keywords. Pulsars: general, ISM: general, radio continuum: stars

1. Introduction

Pulsar radiation typically has strong linear polarization. The observed radiation from pulsars can be affected by Faraday rotation occurring in the interstellar medium. Faraday rotation is quantified by the rotation measure (RM), given by

\[
\psi = \text{RM} \lambda^2,
\]

where \(\psi\) is the linear polarization position angle (PA) and \(\lambda = c/\nu\) is the radio wavelength corresponding to radio frequency \(\nu\). The rotation measure is given by

\[
\text{RM} = 0.810 \int_0^D n_e B \cdot dl,
\]

where \(n_e\) is the interstellar electron density in units of \(\text{cm}^{-3}\), \(B\) is the vector magnetic field in micro-gauss and the integral is over the path to the pulsar.

Long-term variations in PAs possibly result from changes in the polarization of the emitted radiation or may be due to changes in the RM along the path (see Eq. 1.1). RM changes can occur as the path to the pulsar traverses different regions of the interstellar medium (ISM) or in the Earth’s ionosphere due to the diurnal and other changes in the ionospheric total electron content (see Eq. 1.2).

2. Ionospheric RM corrections

Because the Earth’s magnetic field is relatively strong (\(\sim 0.5 \text{ G}\)) and the electron density in the Earth’s ionosphere is relatively high (up to \(10^6 \text{ cm}^{-3}\)), the Earth’s ionosphere makes a significant contribution to the total RM along the path to the pulsar. The contribution of the Earth’s ionosphere to the total RM should be estimated and then subtracted so that the measured RM just represents the interstellar contribution. Yan et al. (2011) used two programs to compute the ionospheric RM in the direction of a given source at a given time. After comparison, they found that the one based on the
International Reference Ionosphere gave the best results. Figure 1 shows an example of the ionospheric correction results using two correction programs.

3. Results and discussion

Yan et al. (2011) reported on temporal variations in the mean position angle and implied RM variations of the 20 millisecond pulsars. Figure 2 shows an example of their results. They found that the largest systematic effect was that due to variations in the Earth’s ionosphere. There are little or no significant long-term variation in RM after ionospheric correction. The authors point out that the interstellar RM variations are unlikely to be due to localized magnetized regions crossing the line of sight because the implied magnetic fields are too high. Most probably they are statistical fluctuations due to random spatial and temporal variations in the interstellar electron density and magnetic field along the line of sight.

Some other authors (e.g. Weisberg et al. 2004, Han et al. 2006) also found apparent time variations in the interstellar RMs of several pulsars. Earlier authors also found correlated RM and DM variations with time for some other pulsars. Hamilton et al. (1977) and Hamilton et al. (1985) studied the variations of RM and DM for the Vela pulsar. They interpret the RM and DM variations as the result of the relative motion of a magnetized filament of the Vela supernova remnant across the line-of-sight. Van Ommen et al. (1997) made a similar analysis for PSRs B1556−44 and B1727−47. Rankin et al. (1988) made a detailed analysis of the RM and DM variations for the Crab pulsar and found correlated variations between 1972 and 1974.

More recently Yuen et al. (2012) analyzed the changes in the PA of PSR J0737−3039A in the Double Pulsar system around the time of its eclipse by PSR J0737−3039B observed

![Figure 1](image-url). PA differences variations after ionospheric corrections for J1643−1224. The upper panel shows the uncorrected differences and the lower two panels show the corrected PA differences using the two methods, with the IRI-corrected data at the bottom. See Yan et al. (2011) for details.
using the Parkes 64-m telescope. They found that differential synchrotron absorption in the closed field-line regions can account for the observed position angle changes during the eclipse. They interpret PA changes after the eclipse as Faraday rotation in the magnetotail of pulsar B. Modeling of the changes in PA after the eclipse with Faraday rotation gives a charge density that is consistent with the Goldreich-Julian value.

4. Acknowledgments

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References

Glitches detected in southern radio pulsars

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Abstract. Parkes pulse arrival-time data for 165 radio pulsars spanning from 1990 to 2011 have been searched for period glitches. Forty-six events out of the detected 107 glitches were found to be new contributions to the entire glitch population of approximately 400 events.

Keywords. stars: neutron - pulsars: general

1. Introduction

Two types of timing irregularities have been hampering a full interpretation of the rotation of neutron stars: timing noise – a random process seen in phase residuals and glitches – a discontinuous increase in the pulse frequency \( \nu \). Glitches are transient events; the most stringent upper-bound known for the timescale of the rising edge of \( \nu \), 40 s, was obtained by Dodson, McCulloch & Lewis (2002) in a high time-resolution observing program for the Vela pulsar. The frequency jump caused by a glitch is actually small with the detected maximum relative size of \( \Delta \nu / \nu \sim 10^{-5} \) (Yuan et al. 2010; Manchester & Hobbs 2011). After a glitch, the slow-down rate \( |\dot{\nu}| \) often partially recovers exponentially, followed by a long-term linear decrease; permanent changes in \( \nu \) and its time derivatives are usually left. These widely observed features are used to model glitches.

2. Observations and Results

Approximately 200 Galactic pulsars have been being observed regularly from 1990 up until now by the 64-m radio telescope at the Parkes Observatory located in western NSW, Australia. Fig. 1 shows 165 pulsars that are in the sample on the \( P - \dot{P} \) diagram. Each pulse time-of-arrival (TOA) for a particular pulsar was obtained every two to four weeks. The data spans for these pulsars range from 5.3 to 20.8 yr with a total of \( \sim 1911 \) yr. By carrying out off-line data reduction, 107 glitches were identified in 36 pulsars and 46 events have not previously been published. Moreover, the recovery fraction \( Q \) and the timescale \( \tau_d \) were measured for 27 exponential decays; post-glitch \( \ddot{\nu} \) were also well measured for those pulsars that exhibit long-term linear increase in \( \dot{\nu} \) between two adjacent glitches. More detailed results are being published in Yu et al. (2012).

3. Discussion

Young pulsars have been thought to be appropriate samples to study neutron-star interiors. It was soon after the discovery of the first glitch that led to the realisation

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that neutron stars are two-component rotators: a rigid-body bulk plus a faster-rotating neutron superfluid (Baym et al. 1969). After twenty-year-observation at Parkes, we now have further found i) the bimodal distribution of the glitch fractional size $\Delta \nu_g/\nu$ has been even clearer (upper panel, Fig. 2), ii) glitches have frequently occurred in the pulsars that have characteristic ages around 10 kyr where, furthermore, large glitches were generally seen, iii) exponential recoveries could be resolved into multiple components corresponding to different timescales and iv) post-glitch $\ddot{\nu}$ values are often positive, are generally larger than the prediction from the magnetic-dipole model and are proportional to the ratio between the slow-down rate and the inter-glitch interval with a proportionality constant $\sim 10^{-3}$. These observations have further probed that neutron stars may suffer the re-configuration of the crustal plate tectonics and/or the substantial release of pinned vortices and, the rotational equilibrium after a glitch established via vortex-drifting may occur in multiple regimes resulting in the observed exponential and linear recoveries.

Nevertheless, the available observations are still not sufficient to entirely interpret the glitch phenomenon. As shown in the lower panel of Fig. 2, the observed fraction $Q$ of the glitch that recovers exponentially has exhibited a bimodal distribution with two peaks locating at approximately 0.01 and 1.0 respectively. For the two-component model, the conservation of angular momentum indicates $Q = I_s/I$, where $I$ is the total moment of inertia of the neutron star and $I_s$ the inertial moment of the superfluid that gradually couples to the effective crust following a glitch. The values of $Q \sim 1$ might have implied that, for some glitches, $I_s$ involved most of the neutron superfluid, though it has been shown that the core superfluid may rigidly couple to the realistic crust in a timescale $\lesssim$ seconds (Alpar, Langer & Sauls 1984; Alpar & Sauls 1988). Moreover, a very large $Q \sim 8.7$ was detected in PSR J1846–0258 recently (Livingstone et al. 2010) which is an even more complicated situation. In addition, peculiar features have also been observed. For instance, quasi-periodic oscillation in timing residuals following a glitch has both been seen in PSR B2334+61 (Yuan et al. 2010) and the Vela pulsar where, moreover,
excess delays were observed for the pulse arrival times measured at a lower frequency (McCulloch et al. 1990). Further exploration on glitch-related phenomena may require intensive observations perhaps with high precision and high observing cadence.

Acknowledgements

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References

Pulsar timing with the DFB at Nanshan

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Abstract. Pulsar timing observations are being carried out with the Nanshan 25-metre radio telescope since 2000. We observe about 300 pulsars, including nine millisecond pulsars, at 1.5 GHz with a cryogenic receiver and digital filterbank. Frequent observations at Nanshan revealed 50 glitches. We detect nine more glitches in the past two years. Timing solutions obtained with the Nanshan telescope for eight radio loud Gamma ray pulsars are presented.

Keywords. stars: pulsars: general, timing

1. Introduction

Pulsar timing has long been used to study the instability of pulsar periods, the distribution and turbulence of the interstellar free electron in Galaxy, as well as pulsar proper motions and hence their velocities. The pulse times of arrival (TOA) of millisecond pulsars (MSP) can be measured much more accurately than normal pulsars and their spin is much smoother, making them as better clock. Moreover they are unique objects which can be used to test the relativity theories, detect the gravitational wave background, and study the evolution of binary.

The Nanshan 25-metre radio telescope operated by Xinjiang Astronomical Observatory (XAO), has been dedicated to monitor pulsars since 2000. In 2010 Jan, a Digital FilterBank (DFB) backend became operational; here we show some results of pulsar timing observations performed with it.

2. Data analysis and Results

Our observations have been made using a dual-channel cryogenic receiver with a bandwidth of 320 MHz centred at 1540 MHz, since 2002 June. There are about 300 pulsars being observed with integration times of 4 – 16 min for each pulsar and three sessions per month. The dedispersion is provided by a 1024×0.5 MHz DFB since 2010. The DFB digitizes band-limited signal in the four Stokes parameters from each of the two orthogonal polarizations. The system sensitivity is 0.4 mJy for 16 min observing time.

The PSRCHIVE and TEMPO2 packages were used to analyze the data (Hotan et al. 2004, Hobbs et al. 2006). Local arrival times were determined by correlating the observed average pulse profiles with standard pulse profiles. The basic timing model for the barycentric pulse phase, $\phi$, as a function of time $t$ is

$$\phi(t) = \phi_0 + \nu(t - t_0) + \frac{1}{2} \dot{\nu}(t - t_0)^2 + \frac{1}{6} \ddot{\nu}(t - t_0)^3$$

(2.1)

where $\phi_0$ is the phase at time $t_0$, and $\nu$, $\dot{\nu}$, $\ddot{\nu}$ represent the pulse frequency, frequency derivative and frequency second derivative.

A comprehensive pulsar monitor program was carried out by the worldwide radio
Table 1. Timing solutions for eight radio loud Gamma ray pulsars.

<table>
<thead>
<tr>
<th>PSR Jν</th>
<th>ν (Hz)</th>
<th>˙ν (×10^{-15} s^{-2})</th>
<th>¨ν (×10^{-24} s^{-3})</th>
<th>Epoch (MJD)</th>
<th>Data range (MJD)</th>
<th>RMS (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0534+2200</td>
<td>29.7021756869(3)</td>
<td>-3.4766.7919(6)</td>
<td>11470(3)</td>
<td>56015</td>
<td>55925–56126</td>
<td>156</td>
</tr>
<tr>
<td>0631+1036</td>
<td>3.4745192097(2)</td>
<td>-1.2642.293(17)</td>
<td>71(6)</td>
<td>55915</td>
<td>55707–56126</td>
<td>1694</td>
</tr>
<tr>
<td>0659+1414</td>
<td>2.39794675570(3)</td>
<td>-3.709272(12)</td>
<td>0.12(17)</td>
<td>55650</td>
<td>55202–56126</td>
<td>1196</td>
</tr>
<tr>
<td>0742–2822</td>
<td>5.99622971186(11)</td>
<td>-6.05240(4)</td>
<td>3.1(7)</td>
<td>55650</td>
<td>55202–56102</td>
<td>1822</td>
</tr>
<tr>
<td>1730–3350</td>
<td>7.1685291201(8)</td>
<td>-4.3544.75(3)</td>
<td>12(3)</td>
<td>55500</td>
<td>55012–56102</td>
<td>8426</td>
</tr>
<tr>
<td>1801–2451</td>
<td>8.002654070(3)</td>
<td>-8.184.4(4)</td>
<td>472(20)</td>
<td>55650</td>
<td>55666–56127</td>
<td>1620</td>
</tr>
<tr>
<td>1835–1106</td>
<td>6.0279662649(6)</td>
<td>-7.478.7(3)</td>
<td>-42(4)</td>
<td>55750</td>
<td>55307–56129</td>
<td>4730</td>
</tr>
<tr>
<td>2043+2740</td>
<td>10.40245141153(15)</td>
<td>-1.334.408(13)</td>
<td>18.5(12)</td>
<td>55580</td>
<td>55202–56102</td>
<td>1154</td>
</tr>
</tbody>
</table>

The pulsar timing community in support the Fermi Gamma ray pulsar commission (Smith et al. 2008). More than 760 pulsar ephemerides from radio observatories are obtained (Abdo et al. 2010), many of these pulsars have high spin-down power (≥ 10^{34} erg/s) and suffer from a high degree of timing noise. Xinjiang Astronomical Observatory joined the program, using the 25-metre dish at Nanshan to monitor about 38 pulsars. Table 1 shows the timing solutions of eight radio loud Gamma ray pulsars. All pulsars but PSR J2043+2740 have glitches reported. Besides the instability of pulsar spin, we also measure the flux and polarization of these pulsars, aiming to study the correlation between their Gamma ray and the radio flux, and help us understand the mechanism of pulsar emission.

Frequent observations at Nanshan revealed 50 glitches up to September 2012 (Wang et al. 2001, Zou et al. 2004, 2008, Yuan et al. 2010a, 2010b, Wang et al. 2012). There are more nine glitches that have not been reported in our earlier works (see Table 2 for details). A new glitch was detected in the Crab pulsar (the fractional jump in frequency ∆ν/∆ν > 34(2)×10^{-9}) in 2011 November with a longer preceding interval of about 1300 days. Figure 1 presents the results of timing analysis of PSR J0631+1036, showing a very large glitch with a frequency jump ∆νg ∼ 11×10^{-6} Hz occurred in 2011. The dashline in Figure 1 indicates the glitch epoch given by the Jodrell Bank glitch catalogue (Espinoza et al. 2011). Most of the jump ∆νg persist beyond the end of the data span. A phase-coherent

Figure 1. The glitch of PSR J0631+1036. (a) Variations of rotational frequency relative to the pre-glitch solution. (b) An expanded plot of variations of rotational frequency. (c) Variations of rotational frequency derivative.
Table 2. Parameters of the nine new detected glitches

<table>
<thead>
<tr>
<th>Psr Name</th>
<th>Glitch Epoch (MJD)</th>
<th>( \Delta \nu / \nu (\times 10^{-9}) )</th>
<th>( \Delta \dot{\nu} / \dot{\nu} (\times 10^{-3}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0534+2200</td>
<td>55875.5(1)</td>
<td>&gt; 34(2)</td>
<td></td>
</tr>
<tr>
<td>J0631+1036</td>
<td>55116(4)</td>
<td>7.2(8)</td>
<td>−1.3(9)</td>
</tr>
<tr>
<td></td>
<td>55702(3)</td>
<td>3278(2)</td>
<td>1.4(2)</td>
</tr>
<tr>
<td>J0742−2822</td>
<td>55020.0(3)</td>
<td>102.1(1)</td>
<td>4.3(2)</td>
</tr>
<tr>
<td>J0922+0638</td>
<td>55140(9)</td>
<td>1256.7(6)</td>
<td>−0.9(3)</td>
</tr>
<tr>
<td>J1801−2304</td>
<td>53307(16)</td>
<td>493.8(5)</td>
<td>0.4(2)</td>
</tr>
<tr>
<td>J1824−1118</td>
<td>54302(15)</td>
<td>2875.7(8)</td>
<td>−13(4)</td>
</tr>
<tr>
<td>J1952+3252</td>
<td>54104(2)</td>
<td>5.7(7)</td>
<td>−0.5(6)</td>
</tr>
<tr>
<td>J1957+2831</td>
<td>54691(4)</td>
<td>5.7(1)</td>
<td>1.3(3)</td>
</tr>
</tbody>
</table>

The fit is consistent with a glitch of \( \Delta \nu_g / \Delta \nu \sim 3.278 \times 10^{-6} \) and a decay model with a time constant \( \tau_d \sim 160 \text{~d} \). It is generally believed that glitch and post-glitch behavior reflect the dynamics of the interior of the neutron star rather than magnetospheric phenomena. Observing glitches and measuring their subsequent decay processes provide one of the few probes of neutron star structure and thus the physics of ultra-dense matter.

Nine MSPs are observed with the Nanshan radio telescope: PSRs J1022+1001, J1518+4904, J1713+0747, J1643−1224, J1600−3053, J1744−1134, J1857+0943, J1939+2134, J2145−0750, seven of which are in binary systems except PSRs J1744−1134 and J1939+2134. The signal obtained with Nanahsn telescope from PSR J1600−3053 is weak, which has S/N of \( \sim 10 \) with 16 min integration time. The profiles of other eight MSPs have S/N of 15 – 50. For the TOAs obtained in one year, the minimum value of timing RMS residuals is several microseconds.

3. Summary

We have presented the timing solutions of eight radio loud Gamma ray pulsars and nine glitches observed with DFB. As many pulsars have no observed glitch over spans of three decades or more, it is valuable to continue timing observations of a large set of pulsars, in order to better characterize glitch properties and hopefully to lead to a better understanding the mechanisms involved. The large number of timing observation at Nanshan with data spanning >10 yr also provide tools to study the pulsar timing noise that is present in most pulsars.

References

FAST low frequency pulsar survey
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Abstract. The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is under construction and will be commissioned in September 2016. A low frequency 7-beam receiver working around 400 MHz is proposed for FAST early science. It will be optimized for a whole FAST sky drift-scan pulsar survey. Simulations show that about 1500 new normal pulsars will be discovered, as well as about 200 millisecond pulsars.

Keywords. pulsars: general

1. Introduction
The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is now under construction. The first light is expected to be in September 2016 (Nan et al. 2011). At the early science phase, a multibeam receiver working at low frequency (< 1 GHz), which has less stringent pointing accuracy requirement, is favored. Such a receiver will even work during the testing phase.

Besides the current 8 sets of receivers, a 7-beam receiver is planned for FAST to do an early pulsar survey. It will work at around 400 MHz with a bandwidth about 150 MHz, which is optimized for whole FAST sky drift-scan pulsar survey. Because the pulsar flux drops down at higher frequency and receiver has smaller beam size at higher frequency, the L-band 19-beam receiver is not sufficient for a whole FAST sky pulsar survey. The 7-beam receiver will be the best option to do this before the Phase Array Feed receiver is available for FAST. This receiver can also be used for a high redshift neutral hydrogen survey and other sciences.

To minimize the risk and to make sure the 7-beam receiver is ready in early 2016, we will use a mature dipole design or horn design like current multibeam receivers such as the Parkes 13-beam and the Arecibo 7-beam receivers.

Outlined below are some tentative technical specifications of the receiver:
- Frequency $f \sim 400$ MHz, bandwidth $\sim 1/3f$, which is feasible by available technology
- System temperature without sky $T_{\text{sys}} \sim 30$ K or less, cooled with lightweight Stirling refrigerator
- Use horn or dipole design
- Light weight, easy to manufacture and inexpensive
- Use 19-beam receiver backends

The 7-beam receiver will be optimized for pulsar and transient survey at early science phase or even earlier. Three probable surveys are listed below.
- Low frequency drift-scan pulsar survey: Detect $\sim 2300$ normal pulsar ($\sim 1500$ new), Detect $\sim 300$ millisecond pulsars (MSPs) ($\sim 200$ new), which is good for gravitational wave detection. Data of one whole FAST sky scan $\sim 2.4$ petabytes. Simulation details are described in Section 2.
M31/M33 pulsar survey: Probably first detection of extragalactic pulsar beyond Magellanic Clouds.

Radio transient survey: Piggyback survey of low frequency drift-scan pulsar survey. Use same data set. Scan the whole FAST sky a few times during early science phase.

2. Pulsar survey simulation

To find the best frequency for the 7-beam receiver, we have done survey simulation using PSRPOP (http://psrpop.sourceforge.net) (Lorimer et al. 2006). The pulsar population generation is similar to Smits et al. (2009).

In drift-scan mode, the integration time is decided by the beam width which is inversely proportional to observing frequency. It is about 40 seconds at 400 MHz. The survey speed also depends on frequency. At 400 MHz, the whole FAST sky (2.3π) will be covered in 2 months. Two working case are considered.

- Spherical surface: The illuminated aperture decreases as frequency increases, \( D_{\text{ill}} \sim 200 \times (f/400 \text{ MHz})^{1/4} \text{ m} \) (Condon 1969). This will be the case at the very early phase before early science phase, when the reflector has just been laid.
- 300 meter diameter parabola surface: The illuminated aperture is a 300 meter diameter parabola. This will be the case at the early science phase.

Since normal pulsars and MSPs constitute different populations, they are discussed separately. First the normal pulsar population is discussed in detail. Results are shown in Fig. 1 and 2.

![Figure 1. Output of one simulation run. Dots are the ~ 100 thousand normal pulsar generated. Circles are the ~ 2300 pulsars detected by FAST at 400 MHz band, ~ 1500 would be new. Bandwidth = 1/3 central frequency is assumed. Reflector surface is 300 meter diameter parabola.](image-url)
Figure 2. Number of normal pulsars detected at different frequencies. Bandwidth is 1/3rd of center frequency and 40s integration is assumed. Left: for spherical reflector surface. The illuminated aperture decreases with frequency, $D_{\text{ill}} \sim 200 \text{ m} \times (f/400 \text{ MHz})^{1/4}$ (Condon, 1969); A maximum of 1200 pulsars will be detected. Right: for reflector with a 300 m-diameter parabolic illuminated surface. A maximum of 2300 pulsars will be detected. Since there are already $\sim 800$ known pulsars in the FAST sky, a total of 1500 new normal pulsars are expected to be discovered. The number of detected pulsars peaks around 500 MHz, but does not vary much when the center frequency is in the range 400 to 700 MHz. Considering number of pulsars detected and survey speed, the lower frequency end 400 MHz is favored.

3. Discussion

MSPs are different to normal pulsars, having e.g. a different spectral index, and spatial distribution. A spectral mean $-1.6$ with deviation 0.35 is used by Smits et al. (2009). We find that using these values will underestimate MSPs detected in the Parkes 70 cm survey. We then treat spectral index and spectral index deviation as free parameter, and find in the parameter space where the simulation agrees with both Parkes multibeam survey and 70 cm survey. The result favor steeper spectral index or larger spectral index deviation. Details will be presented in a later paper.

A pulsar survey is sensitive to RFI, which should be carefully considered. The overall RFI situation at FAST site is good around 400 MHz. Only a few narrow-band RFI instances exist. The final frequency and bandwidth of the receiver will be decided after new measurements of the RFI.

Acknowledgments

The 7-beam receiver was initially proposed by Jim Condon. We appreciate the valuable comments and suggestions from the pulsar community and FAST group, and help from Fredrick Jenet, Duncan Lorimer and Roy Smits. This work is supported by the National Natural Science Foundation of China (11103045) and by China Ministry of Science and Technology under State Key Development Program for Basic Research (2012CB821800).

References


Changes in Polarization Position Angle across the Eclipse in the Double Pulsar System

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Abstract. We investigate the changes in polarization position angle in radiation from pulsar A around the eclipse in the Double Pulsar system PSR J0737-3039A/B at the 20 cm and 50 cm wavelengths using the Parkes 64-m radio telescope. The changes are \( \sim 2 \sigma \) during and shortly after the eclipse at 20 cm but less significant at 50 cm. We show that the changes in position angle during the eclipse can be modelled by differential synchrotron absorption in the eclipse regions. Position angle changes after the eclipse are interpreted as Faraday rotation in the magnetotail of pulsar B. Implied charge densities are consistent with the Goldreich-Julian density, suggesting that the particle energies in the magnetotail are mildly relativistic.

Keywords. binaries: eclipsing — polarization — pulsars: individual (PSR J0737-3039A, PSR J0737-3039B)

1. Introduction

The almost edge-on orbit in the Double Pulsar system, which consists of two pulsars (pulsar A and pulsar B), results in a 30-second eclipse observable once each orbit when pulsar A moves behind pulsar B at orbital longitude of \( \sim 90^\circ \) measured from the ascending node (Lyne et al. 2004). The magnetosphere of pulsar B is truncated because of the strong relativistic wind from pulsar A (\( \dot{E}_A/\dot{E}_B \sim 3500 \)) forming a magnetotail that probably reaches a distance of several semi-major axes of pulsar B’s orbit (the semi-major axis is \( 4.5 \times 10^8 \) m) (Arms et al. 2004). Because of the orbital motion, the magnetotail is curved behind pulsar B. Across the eclipse regions, pulsar A’s radiation passes through pulsar B’s truncated magnetosphere and interacts with the plasma during an eclipse, then, as the two pulsars advance in orbit away from the superior conjunction, pulsar A’s radiation begins to traverse the magnetotail. In this paper, we investigate the changes in polarization position angle in radiation from pulsar A during and around the eclipses.

2. Data analysis and Results

The data of interest were taken at 20 cm and 50 cm using the Parkes 64-m radio telescope with sub-integration time of 30 s. The \texttt{psrchive} software suite (Hotan et al. 2004) was used for data analysis including interference rejection and calibration. Data were...
summed in frequency using the corrected rotation measure, +112.3 rad m$^{-2}$ (Manchester et al. 2010). We obtained 38 files at 20 cm and 13 at 50 cm with good quality data. To improve the signal-to-noise ratio, we summed the files in each band, binning the results in orbital phase with phase bins of $\sim 0.7^\circ$ or $\sim 18$ s in width. Finally, Stokes parameters were summed across the main pulse and interpulse to form the average Stokes parameters for each orbital phase bin.

We consistently detected changes in position angle during and shortly after an eclipse at both wavelengths (Figure 1). Inspection of the 20 cm curve in the eclipse region shows that the position angle decreases during the ingress phase then rises to its maximum value during egress phase with a change of approximately $\sim 6^\circ \pm 3^\circ$ and $\sim 3^\circ \pm 2^\circ$ respectively relative to the mean baseline level. It remains high for the following phase bin, then drops back to the baseline value. There are also changes in polarization angle in the corresponding regions during the eclipse at 50 cm, but the uncertainties are larger. Nevertheless, the position angle changes shortly after the eclipse are consistent with those at 20 cm. We confirmed our results by randomly partitioning the 20 cm files into two, three or four subsets either randomly or chronologically, which show similar patterns, i.e., a decrease in position angle during ingress followed by an increase during egress.

3. Mechanisms to change the polarization position angle

**Eclipse region: differential synchrotron absorption.** With our 18s averaging time, the direction of the differential synchrotron absorption relative to the incoming radiation can be approximated by averaging the magnetic field perpendicular to the rotation and magnetic axes to zero leaving a net magnetic field along B’s rotation axis. The position angle of the transmitted radiation changes with increasing optical depth, $\tau_\nu = \alpha_\nu L$, with the position angle moving toward the angle of the projected magnetic field. Here $L$ is the effective path length through the absorbing medium and $\alpha_\nu$ is the polarization-averaged synchrotron absorption coefficient for a relativistic thermal distribution of particles (Lyutikov & Thompson 2005). Denoting $\chi_0$ and $\chi_\nu$ to be the incident and emergent polarization angles relative to the projected magnetic field direction, and assuming $\chi_0 = 45^\circ$ gives an order of magnitude change in polarization or position angle,
$\Delta \psi = \chi_\nu - \chi_0$, of 10° at 20 cm. This is consistent with our measurements suggesting that differential synchrotron absorption in the closed field-line regions can plausibly account for the observed position angle changes during the eclipse.

**Magnetotail: Faraday rotation.** Net magnetic field in the line of sight results from the large inclination angle in pulsar B and the misalignment between its rotation axis and the orbital normal, which result in an asymmetric field structure in the magnetotail as the pulsar rotates within the confining magnetosheath (Spitkovsky and Arons 2004). Assuming magnetic field scales as $r^{-2}$ up to $L/2$ and as $r^{-1}$ at larger distance in the magnetotail ($L \approx 1.5 \times 10^{-8}$ pc is the semi-major axis of pulsar B’s orbit), and with $\Delta \psi_{50} = 0.81 L (n_e B) \lambda^2 \sim -5^\circ$, gives $n_e \sim 40$ cm$^{-3}$, which is comparable to the estimated corotation charge density (Goldreich and Julian 1969) of $n_e \sim 20$ cm$^{-3}$. This suggests that Faraday rotation may be responsible for the changes in position angle away from the eclipse region, which also implies that the charged particles are no more than mildly relativistic. Direct generation of mildly relativistic pairs is favored for magnetic fields with $0.02 B_{cr} < B < 0.1 B_{cr}$, where $B_{cr} \approx 4.9 \times 10^{13}$ G is the critical field strength (Weise & Melrose 2002).

4. Conclusions

We have observed changes in polarization position angle in radiation from pulsar A during and shortly after the eclipse in the Double Pulsar system at 20 cm and 50 cm wavelengths. These changes can be accounted for by differential synchrotron absorption and Faraday rotation respectively with the latter implying that pairs must be created directly in nonrelativistic regime.

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Questions on accreting mass and minimum magnetic field of millisecond pulsars

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Abstract. About 0.2 solar mass is absorbed by the millisecond pulsar (MSP) at the binary accretion phase, while the polar magnetic field of MSP is diluted to a magnitude of order $10^{8.5}$ Gauss, which is proportionally related to the mass accretion rate. It is found that the minimum magnetic field of MSP can be as low as $10^7$ Gauss if the accretion rate of the binary system reaches its the minimum value of $10^{15}$ g/s. This bottom field has nothing to do with the MSP initial field. Some questions on MPSs are proposed and answered.

Keywords. Pulsar, neutron star, mass, magnetic field

1. General picture of MSP evolution
The millisecond pulsar (MSP) is formed in the binary accretion phase, while the neutron star (NS) accretes matter from its companion. The magnetic field and spin period are both decreased to the values of $10^{8.5}$ Gauss and several milliseconds (Wijnands & van der Klis 1998), if the system absorbed the mass of about 0.2 solar mass (Bhattacharya & van den Heuvel 1991; Wang et al. 2011; Zhang et al. 2011; Alpar et al. 1982; Tauris 2012). Then the conventional NS is formed from the supernova explosion, while a high magnetic field of about $10^{11-13}$ G and spin period of about 20-30 milliseconds, which can be seen from the observed pulsar data of ATNF (Manchester et al. 2005). In a NS binary system, if the accretion mass of $\sim 0.01M_\odot$ is accreted from the companion, a NS can be spun up to several tens of milliseconds, while its magnetic field will be decayed to $\sim 10^{9-10}$ G, e.g. the double pulsar system (Lyne et al. 2004; van den Heuvel 2004). Therefore, more mass accreted and less magnetic field of NS achieved (Zhang & Kojima 2006). In this short paper we present some enquiries and basic conclusions on MSP evolution.

2. The bottom field and minimum field of MSP
During the accretion phase, if the NS field is high, then the accreting MHD materials flow along the polar field lines to fall on the NS surface, while the MHD matter is piled-up at the magnetic polar cap and it flows from the polar cap to the equator, while the MHD flow drags the field lines asides to dilute the polar field strength (Zhang & Kojima 2006). The accretion flow continues until the field lines are all trapped into the star, at where the magnetosphere of NS equals to the NS radius, which can give a bottom field ($B_f$) of NS of about $\sim 10^{8.5}$ G after the system accretes about 0.2 solar mass,

$$B_f \simeq 10^{8.5}(G)(\dot{M}/10^{18} g/s)^{1/2}, \quad (2.1)$$

where $\dot{M}$ is the accretion rate. If the accretion rate is at its minimum value of $10^{15}$ g/s, then the minimum field strength of MSP is obtained as

$$B_{\text{min}} \simeq 10^7(G)(\dot{M}/10^{15} g/s)^{1/2}. \quad (2.2)$$

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From the known derived fields of MSPs, we find the minimum value of field is about $10^{7.5}$ G (Manchester et al. 2005), which is very close to our theoretical result. Moreover, the field and spin evolutions with the accreted mass can be given, and both decay until the bottom values after system accretes about 0.2 solar mass.

3. Does NS field decay after the accretion phase?

Generally, from a long-term point of views, the field decays while the accreted mass is added, and field has little decay if the accretion phase stops. The evidence for this can be found from the binary pulsar system (NS+white dwarf), where the temperature of WD is observed that implies a cooling age of system, which gives a conclusion that the field has little decay at the time scale of $10^9$ yr if there is no accretion.

4. The accretion must result in the field decay of NS?

From the accretion induced field decay model (Zhang & Kojima 2006), if the accretion MHD dragging at the polar cap is totally frozen, then all accreted matter contributes to the field decay. In case the MHD frozen efficiency is not 100%, for instance 1%, then 0.2 solar mass accretion only makes field decay to $10^{10}$ G. If this efficiency is as low as 0.01%, then 0.2 solar mass accretion makes the little field decay. The frozen efficiency may be related to the magnetic inclination angle of NS, then detail of which is still in consideration. Say, some NSs may have little field decays after accreting 0.2 solar mass.

5. The role of accretion rate on MSP field

The accretion mass has a dominant role in MSP evolution; the accretion rate is also a factor. From X-ray NS, the average rate is about $\dot{M}/10^{17}$ g/s. If the rate is less than $\dot{M}/10^{15}$ g/s, then the Ohmic decay velocity will be faster than the accretion deepen-in velocity, while the accretion cannot bury the field into the NS core region. Therefore, a minimum accretion rate is needed for the field decay. The high accretion rate corresponds to a high bottom field, e.g. Eddington rate will correspond to a bottom field of $10^{8.5}$ G.

6. The mass of MSP: 1.6 solar mass on average

Two decades ago, researchers often thought that the mass of MSP should be usually as high as 2.0 $M_\odot$. However, the recent statistics of 65 measured NS masses indicates that the average mass of MSP is only 1.6 solar mass (Zhang et al. 2011), comparing to the mass of slow rotating NS of about 1.4 solar mass, and MSP seems to absorbs only 0.2 solar mass in average. Then a question arises where it goes the one solar mass of WD companion? Does an MSP only accrete 20% mass of its companion? After the spinning-up of an MSP, some accreted mass is finally rejected from the NS? The EOS of MSPs is different from that of normal NSs? These questions are still open.

7. Alternative possibility: MSP formation from AIC?

MSPs are usually thought to be formed by a spin-up of NS in a binary system by accretion. Then, the idea that an MSP forms in an accretion induced collapse of a WD is not automatically excluded. What is a specialty of an MSP from AIC? The mass of an MSP by AIC should be less than Chandrasekhar limit, e.g. 1.3 solar mass. From the measured masses of MSPs (Zhang et al. 2011), it really exist 3 MSPs with the masses less
than 1.3 solar masses. Then we cannot be sure if these low mass MSPs are formed in the low mass states, e.g. one solar mass, or by AIC processes. More MSP masses are needed, by which we can distinguish the details of MSP mass and its formation processes.

8. Bottom magnetic field of MSP has no relation to its initial field

The evolution history of MSPs can be understood in this way: the initial magnetic field of NS can be as high as \( B \sim 10^{13} \) G, and it can decay to \( B \sim 10^8 \) G, after accreting \( \sim 0.2 M_\odot \), while NS magnetosphere is the same size of NS. In other words, the bottom field of MSP is determined by the condition that the radius of NS magnetosphere equals the radius of NS. This fact means that the bottom field is nothing to do with its initial field strength! From the field and spin period distributions of MSPs and pulsars (Wang et al. 2011), we notice that the field distribution of normal pulsars ranges at \( B \sim 10^{11-13} \) G, then that of MSPs ranges narrowly at \( B \sim 10^{8-9} \) G, which should be the effect of bottom field, at where the fields stops but is no relation to its born field. The significant application of bottom field is that the high and low luminosity X-ray sources, Z and Atoll, share the similar kHz QPO frequencies, indicating the similar magnetosphere radii at scale of NS radii (Zhang 2004; Zhang et al. 2006)

9. Magnetic structure of MSP: strong magnetic domain \( 10^{14-15} \) G?

If accretion drives decays of the magnetic field of an MSP, is the magnetic structure altered too? Yes; the polar field lines of MSP are dragged to the equator region, where all field lines are sunk into the core region of NS (Zhang & Kojima 2006). Thus, the estimation indicates that the polar field of MSP is as low as \( 10^8 \) G, the equator field, beneath the NS surface, can be as high as \( 10^{13-14} \) G, and the core field of NS may be even higher that \( 10^{14} \) G, e.g. \( 10^{15} \) G. In other words, the MSP magnetic structure is redistributed after accretion. The leaked-out field lines of the MSP may produce the effect that the local field at the magnetic equator should be much higher than \( 10^8 \) G, e.g. \( 10^{11-12} \) G, then the global field of MSP is dominated by a polar field with the low value \( 10^8 \) G. Radio observations of MSPs should reflect their low field characteristic, while the X-ray observation may show their local strong fields. The complex magnetic structure of MSP may be noticed from the high energy emissions, e.g. Fermi, in the future.

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Mutual influence of magnetic field decay and thermal evolution of rotational neutron stars

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Abstract. The effect of magnetic field decay on the chemical heating and thermal evolution of neutron stars is discussed. Our main goal is to study how chemical heating mechanisms and thermal evolution are changed by field decay and how magnetic field decay is modified by the thermal evolution. We show that the effect of chemical heating is suppressed by the star spin-down through decaying magnetic field at a later stage; magnetic field decay is delayed significantly relative to stars cooling without heating mechanisms; compared to typical chemical heating, the decay of the magnetic field can even cause the temperature to turn down at a later stage.

Keywords. stars: evolution, stars: magnetic fields, stars: neutron, stars: rotation, radiation mechanisms: thermal.

1. Introduction

Neutron stars (NSs) are detected as pulsars. Their regular pulsations in the radio, X-ray, and/or optical bands are produced by a strong magnetic field being turned around at the stellar rotation period. It’s widely accepted that a rapidly spinning neutron star loses its rotational energy by magnetic dipole radiation; thus the rotational evolution of isolated NSs are determined by the evolution of its magnetic field (Becker 2008, Glendenning 2000). NSs also are very hot at birth, with temperatures well above 10¹⁰K. This heat is radiated away mainly by neutrinos from the interior during the first million years or so (the neutrino cooling era) while later the emission of photons from the surface dominates the cooling of the star (the photon cooling era). This photon luminosity and its change with time depend on the properties of dense matter in the interior of NSs, its magnetic field and heating mechanisms (Becker 2008, Glendenning 2000). For example, the heating energy of chemical heating comes from the rotational energy which is converted into heating by storing rotational energy in terms of chemical energy (Reisenegger 1995, Fernández & Reisenegger 2005). Observations of thermal radiation provide important information about the state of matter above and below nuclear density as well as for the magnetic field (e.g. Yakovlev et al. 2001, Zheng & Zhou 2006, Zhou et al. 2007 and references therein). Goldreich & Reisenegger (1992) discussed the processes which promote the dissipation of magnetic energy in NSs, while the decaying magnetic field of magnetar and how this decay affects the cooling of the stars is studied in Heyl & Hernquist (1997, 1998) and Miralles et al. (1998).

In summary, the rotational, magnetic field and thermal evolution of NSs are coupled, and influence each other. Here we discuss the coupling evolution thermal evolution and...
magnetic field decay of rotating NSs, focusing especially on the effect of the decaying magnetic field on chemical heating mechanism.

2. The models

Several physical mechanisms have been proposed for magnetic field decay in NSs: ohmic decay, ambipolar diffusion and Hall drift (Goldreich & Reisenegger 1992). Depending on the strength of the magnetic field, each of these processes may dominate the evolution. A simple differential equation can be used to describe the dipole magnetic field decay (Goldreich & Reisenegger 1992, Heyl & Hernquist 1997, Heyl & Hernquist 1998, Miralles et al. 1998):

\[ t_{\text{ohmic}} \sim 2 \times 10^{11} \frac{L^2}{T^2} \left( \frac{n}{n_0} \right)^3 \text{yr}, \]

\[ t_{\text{ambip}}^* \sim \frac{5 \times 10^{15}}{T^2} \text{yr} + t_{\text{ambip}}^* t_{\text{Hall}} \sim 5 \times 10^8 \frac{L^2 T^2}{B^2} \left( \frac{n}{n_0} \right) \text{yr}. \]

Here we take \( n = 0.56 \text{ fm}^{-3}, \rho_c = 1.2 \times 10^{15} \text{ g cm}^{-3}, x_{eq} = 0.07, R = 10.4 \text{ km}; \) these are the typical values for a 1.4\( M_\odot \) NS modeled with equation of state “AV14+UVII” (Wiringa et al. 1998). In that equation of state, the NS cools through modified URCA processes. With the given initial spin period, temperature and magnetic field, we solve the following equations numerically (Reisenegger 1995):

\[ \frac{d\delta\mu}{dt} = -E_{xx} \left( \frac{\alpha n E_{xx}}{E_{xx}} \frac{\Omega}{\Omega} + \frac{\Omega}{\n} \right), \]

\[ \frac{dB}{dt} = -B_{p} \left( \frac{1}{t_{\text{ohmic}}} + \frac{1}{t_{\text{ambip}}} + \frac{1}{t_{\text{Hall}}} \right), \]

\[ \dot{E}_B = -\frac{dE_B}{dt} B_{p} R^3, \dot{E}_\gamma = \frac{\Gamma \delta\mu}{\n} - \dot{E}_\gamma + \frac{m_{n}}{\n} \dot{E}_B, \frac{d\Omega}{dt} = -\frac{2\dot{E}_B}{3cT^2} \Omega^2(t) B^2(t). \]

3. Discussions and Conclusions

The results are presented in Fig. 1. Our work shows that: the thermal evolution delays the decay of the magnetic field through heating effects; while the decaying magnetic field even makes the surface temperature lower at photon cooling era through rotation and chemical evolution. The heating energy of chemical heating comes from the rotational energy which is converted into heating by storing rotational energy in terms of chemical energy. As follows from

\[ \frac{d\delta\mu}{dt} = -E_{xx} \left( \frac{\alpha n E_{xx}}{E_{xx}} \frac{\Omega}{\Omega} + \frac{\Omega}{\n} \right), \]

the evolution of \( \delta\mu \) is closely connected with rotation evolution (through angular velocity directly or indirectly). In the photon cooling era \( \delta\mu \) becomes small, since the spin-down of the star has been delayed by the decaying magnetic field. Meanwhile, the surface temperature of the star also becomes lower in the same era. These show that: the effect of chemical heating has been suppressed by the spin-down of the stars through decaying magnetic field at a later stage. When we discuss the cooling of NSs, we should take into account the coupling effect of decaying magnetic field and spin-down of NSs on the heating mechanisms.

We are aware of the fact that our model is simplified and can be improved in many respects. Firstly, a more realistic NS model should be considered more carefully. Secondly, a more elaborate model of the magnetic field evolution may be used, instead of a simple model formulated in Sect. 2, in order to take into account the variation of the magnetic field of the stars. Thirdly, the reaction rates in superfluid neutron stars are suppressed at low temperatures (Yakovlev et al. 2001) and superfluidity makes ambipolar diffusion inefficient (Glampedakis et al. 2011). These arguments suggest that the coupling evolution of a superfluid neutron star should be studied carefully in future work. In spite of some shortcomings, our simple model shows the qualitative importance of the coupling evolu-
Figure 1. a: Time evolution of the decaying magnetic field with chemical heating and magnetic field dissipation heating (solid lines). The curves for decaying fields which are cooling through the modified URCA processes without any heating effects (dotted lines); b: Evolution of $\frac{\delta \mu}{\pi k_B}$ for different initial magnetic field; c: Evolution of the surface temperature for different initial magnetic field. d: Time evolution of normalized angular velocity with different initial magnetic fields. The solid lines are for decaying fields with chemical heating and magnetic field dissipation heating. The dotted lines are for the standard magnetic dipole braking model.

olution of thermal, rotational and magnetic field of NSs, especially the chemical heating have been suppressed by the decaying magnetic field. Future investigations will consider a consistent evolution including the geometry of the magnetic field, the structure of NSs, and compared with the thermal emission observation data.

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