Neutron Star Masses

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IAU XXVIII General Assembly, Beijing, August 2012

This set of slides differs slightly from the set presented in the conference. Some redundant figures have been deleted.

Outline
(a) Introduction
(b) The most massive neutron stars
(c) Masses of neutron star sub-populations
(d) Conclusion
Neutron Star Masses

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Pulsar in Keplerian orbit observed via pulsar timing
Parameterized by: orbital period, projected semi-major axis, eccentricity, angle of periastron, time of periastron passage

Ambiguity 1: orbit inclination is unknown.

orbit not edge-on; observed $\Delta t$ same as edge-on case, but orbit is larger
Pulsar in Keplerian orbit observed via pulsar timing
Parameterized by: orbital period, projected semi-major axis,
eccentricity, angle of periastron, time of periastron passage

Ambiguity 2: Companion mass and orbit size are unknown.

Companion might be heavy star in small orbit or light star in a large orbit

Because of these ambiguities, pulsar timing observations of a Keplerian orbit does not tell us everything we want to know about the orbital system. In particular, we cannot infer either the pulsar mass, $m_1$, or the companion mass, $m_2$.

We need two additional measurements.

$$\left(\frac{2\pi}{P_b}\right)^2 \frac{(a_i \sin i)^3}{G} = f_i = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$
Precession:
\[ \dot{\omega} = 3 \frac{G^{2/3}}{c^2} \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{1 - e^2} \left[ (m_1 + m_2) \right]^{2/3} \]

Shapiro Delay:
\[ \Delta t = 2 \frac{G}{c^3} m_2 \ln \left[ 1 - \sin i \sin (\varphi - \varphi_0) \right] \]

Grav Redshift/Time Dilation:
\[ \nu = \frac{G^{2/3}}{c^2} \left( \frac{P_b}{2\pi} \right)^{1/3} e \frac{m_2 (m_1 + 2m_2)}{(m_1 + m_2)^{2/3}} \]

Gravitational Radiation:
\[ P_b = - \left( \frac{192\pi}{5} \right) \frac{G^{5/3}}{c^5} \left( \frac{P_b}{2\pi} \right)^{-5/3} \left( 1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right) \frac{1}{(1 - e^2)^{5/2}} \frac{m_1 m_2}{(m_1 + m_2)^{2/3}} \]

Second Orbit:
\[ \frac{m_1}{m_2} = \frac{a_1 \sin i}{a_2 \sin i} \]
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Figure: Lattimer & Prakash 2004 (Science 304: 536)
Eccentric MSP binary PSR J1903+0327
Champion et al. 2008 (Science 320: 1309)
Freire et al. 2011 (MNRAS 412: 2763)

Fully recycled $P=2.15$ ms
Eccentric $e=0.44$
Main sequence companion
$\Rightarrow$ unique evolution

Precession
$\bullet 0.0002400(2)^\circ/yr$
$\Rightarrow m_1+m_2=2.70\pm0.03 M_\odot$
Shapiro Delay
$\bullet$ Inclination $77.47\pm0.15^\circ$
$\bullet m_2=1.029\pm0.008 M_\odot$

$m_1=1.667\pm0.021 M_\odot$
Pulsar-White Dwarf binary PSR J1614-2230
Demorest et al. 2010 (Nature 467: 1081)

- Fully recycled P=3.15 ms
- Circular e~10^{-6}
- White dwarf companion
  - 8.7 day orbit

- Shapiro delay
  - Inclination 89.17±0.02°
  - $m_2=0.500±0.006\, M_\odot$

- $m_1=1.97±0.04\, M_\odot$
Eclipsing binary PSR B1957+20
van Kerkwijk, Breton, & Kulkarni 2011 (ApJ 728: 95)

Optical observations
• Light curve \(\Rightarrow\) inclination
• Spectra \(\Rightarrow\) orbit \(\Rightarrow\) \(m_1/m_2\)

\[ m_1 = 2.40 \pm 0.12 \, M_\odot \]
Figure: Jim Lattimer
stellarcollapse.org/nsmasses
Eccentric globular cluster pulsars
47 Tuc I, 47 Tuc J, M5B, NGC6440B

NGC6440B
• Precession: $0.00391\pm0.00018^\circ/yr$
  $\Rightarrow m_1=2.92\pm0.20 M_\odot$
• Inclination: Uniform a priori distribution of $\cos i$
  $m_1=2.74\pm0.21 M_\odot$

Same reasoning for 47 Tuc I, 47 Tuc J, and M5B yields relatively large $m_1$ values.
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Birth Mass

+ 

Accreted Mass (for recycled pulsars)

= 

Observed Mass
Bayesian analysis of all pulsar masses.

All pulsars: $1.35 \pm 0.04 M_\odot$

Model cumulative distribution of pulsar masses, test with Kolmogorov-Smirnov and Anderson-Darling test. Six NS-NS systems and two NS-WD systems.

Two populations:
• $1.246 \pm 0.008 \text{M}_\odot$ (four pulsars)
• $1.345 \pm 0.025 \text{M}_\odot$ (ten pulsars)

Argued that the low-mass and high-mass populations are consistent with electron capture supernovae and iron core collapse supernovae, respectively.
Bayesian analysis of NS-NS systems and NS-WD systems.

• NS-NS: 1.35±0.13M⊙
• NS-WD: 1.50±0.25M⊙

Argued that the difference in mass ranges was due to accretion in the formation of the NS-WD systems.
Bayesian analysis segregating categories of NS based on evolution and accretion history.

- All NS-NS: $1.33\pm0.06M_{\odot}$
- Recycled NS-NS: $1.35\pm0.06M_{\odot}$
- Non-recycled NS-NS: $1.32\pm0.07M_{\odot}$
- Fully recycled: $1.48\pm0.20M_{\odot}$
- Slow or Accreting: $1.28\pm0.24M_{\odot}$

Conclude that tight mass distribution of NS-NS systems requires relatively rare NS formation channel.
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The future I. New millisecond pulsar discoveries.

Session 1: Pulsar Discovery I
10:35 The HTRU surveys for pulsars & fast transients  Michael Keith
10:55 The PALFA Survey: Going to great depths to find radio pulsars  Patrick Lazarus
11:15 The hunt for new pulsars with the Green Bank Telescope  Ryan Lynch
11:35 New results from LOFAR  Ben Stappers
11:55 Conducting the deepest all-sky pulsar survey ever:
   The All-Sky High Time Resolution Universe Legacy Survey  Cherry Ng
12:15-12:30 A search for pulsars in the central parsecs of the Galactic Center  Andrew Siemion

Session 3: Pulsar discovery II and Poster Session
16:00 Fermi LAT Searches for gamma-ray pulsars  Pablo Saz Parkinson
16:20 Radio counterparts of gamma-ray pulsars  Lucas Guillemot

MSP discoveries by year

Cumulative MSP discoveries

Galactic (non-cluster) MSPs. Data from Dunc Lorimer, astro.phys.wvu.edu/GalaticMSPs
The future II.
Wide bandwidth high precision timing

Arecibo Mark4
1998-2006
10 MHz bandwidth
The future II.
Wide bandwidth high precision timing

GASP(GBT)/ASP(Arecibo)
2005–2012±
64 MHz bandwidth
The future II.
Wide bandwidth high precision timing

GUPPI (GBT), PUPPI (Arecibo)
2011±
800 MHz bandwidth
Summary

- Precise NS mass measurements of $\sim 2M_\odot$ are pushing limits of equation-of-state models

- NS sub-population masses
  - Unrecycled NS in NS-NS binaries: relatively light; narrow distribution
  - Mildly recycled NS in NS-NS binaries: slightly heavier; narrow distribution
  - Fully recycled NS: significantly heavier; wider distribution
  - Unrecycled NS not in NS-NS binaries: relatively wide distribution?

- Dozens of new discoveries, coupled to vastly improved instrumentation, promise many more mass measurements in the coming years.