

Pulsar Wind Nebulae

On their Evolution and Diversity

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IAU Symposium 291

Beijing, 20-24 Aug. 2012



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Walter Baade

The Most “famous”

that confirmed B&Z’s 1934 prediction
that neutron stars are born in SNe

The brightest and the closest..

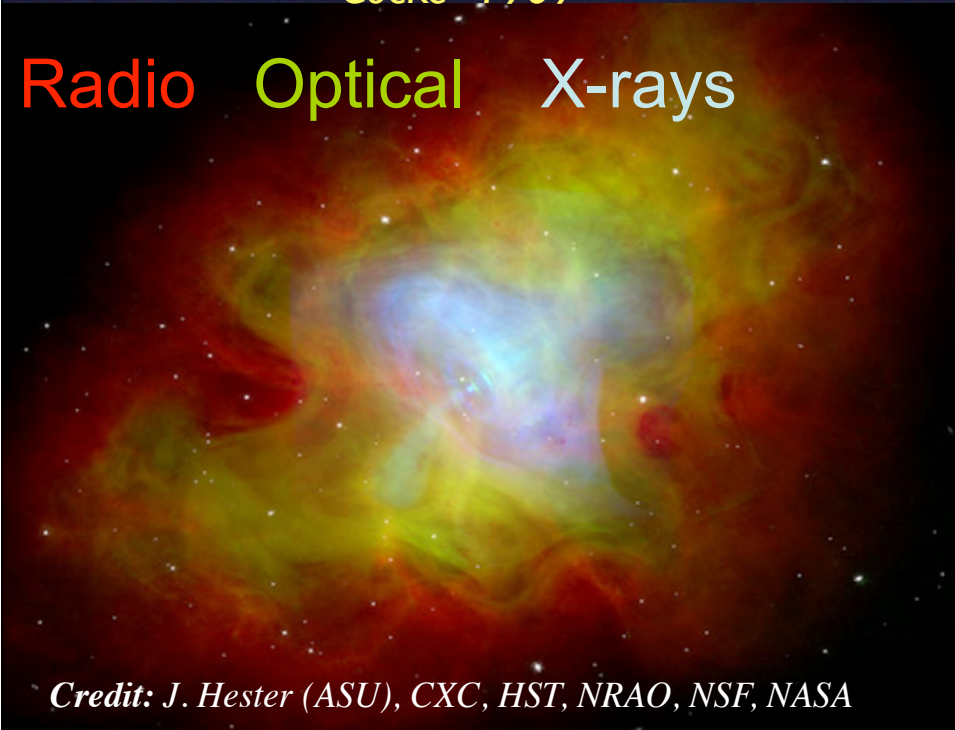


Fritz Zwicky

Crab Pulsar NP0532

*Staelin & Reifenstein (1968), Lovelace+ (1968),
Cocke+1969*

Radio Optical X-rays

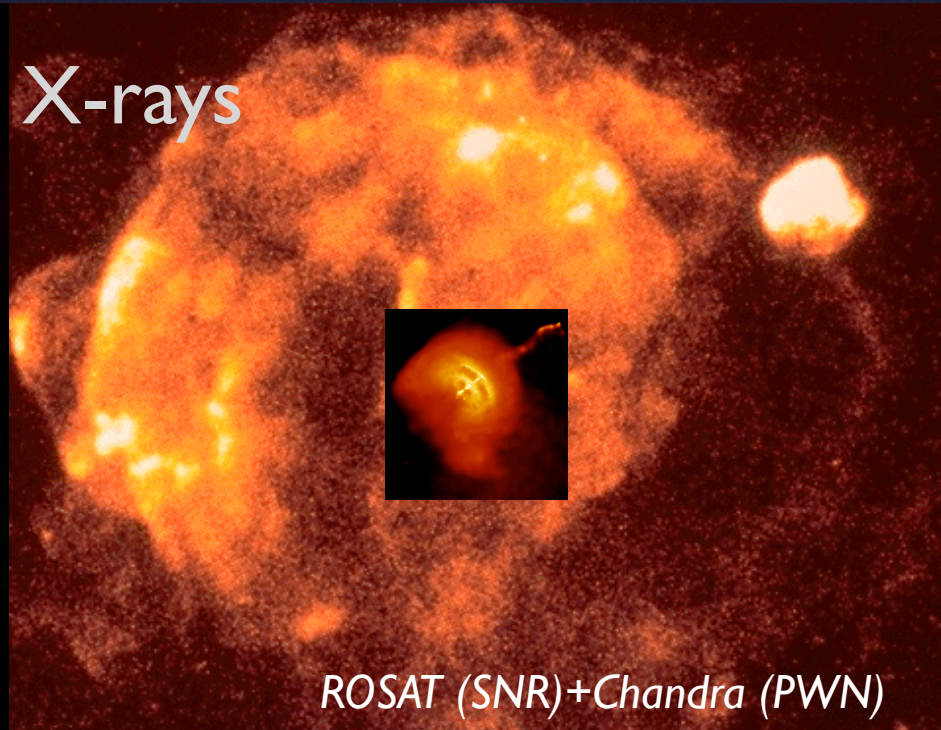


Credit: J. Hester (ASU), CXC, HST, NRAO, NSF, NASA

Vela PSR0833-45 (89ms)

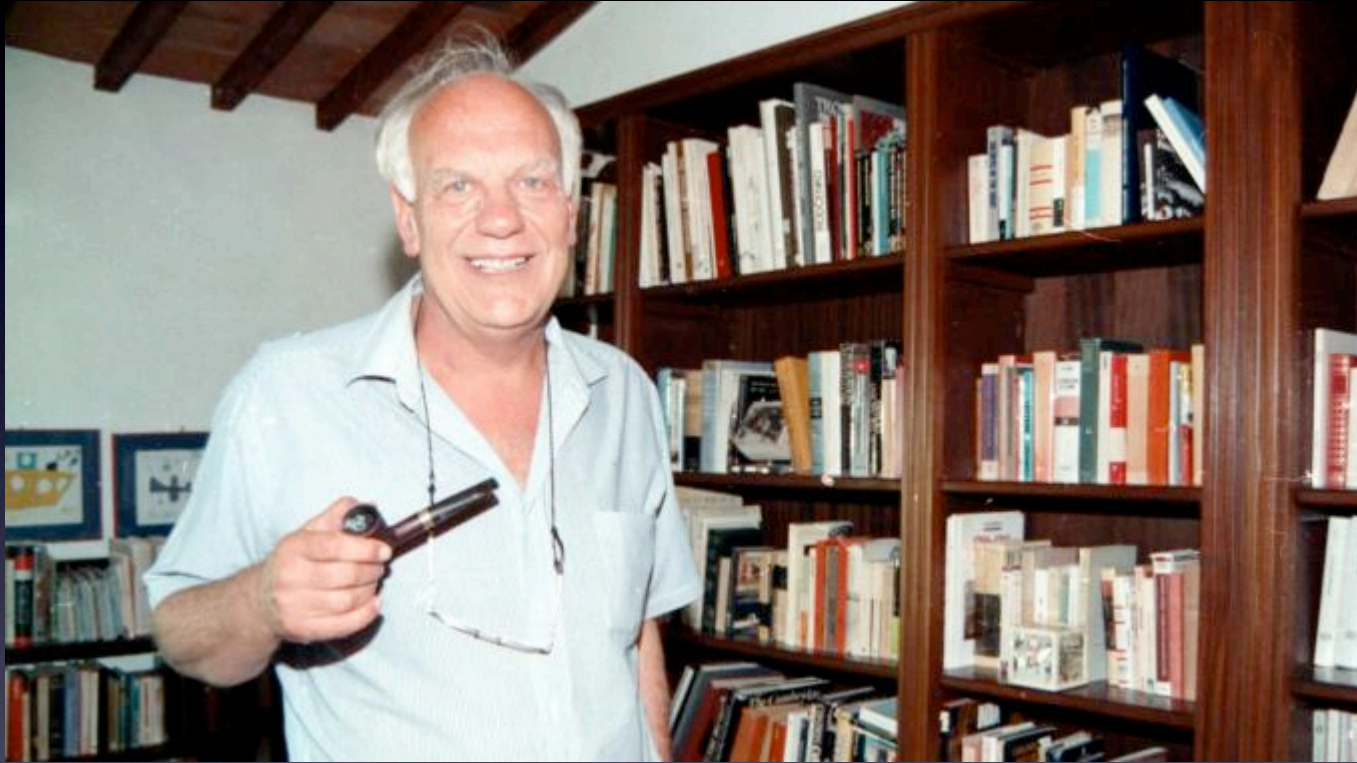
Large+ (1968)

X-rays



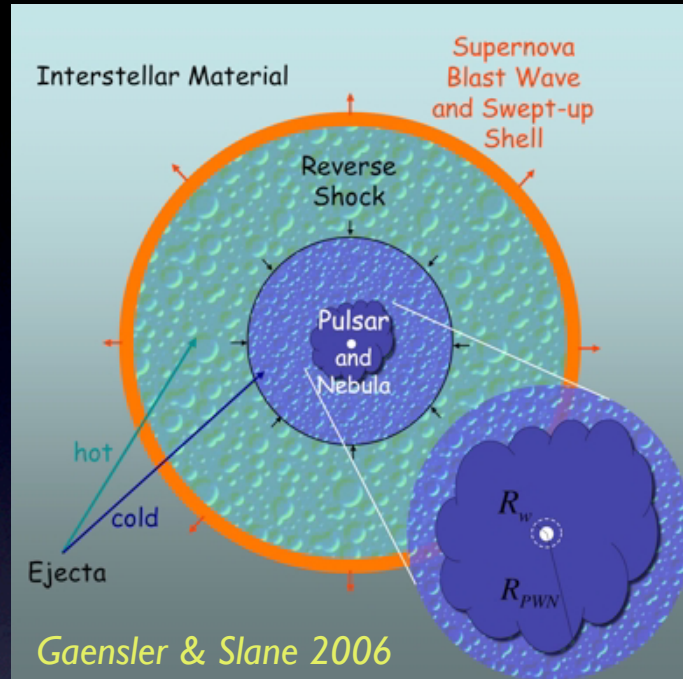
ROSAT (SNR)+Chandra (PWN)

Pulsars are Rotating Neutron Stars with strong B: Magnetized particle wind

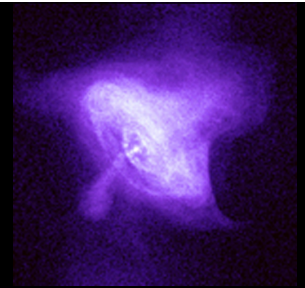


(late) **Franco Pacini**: 1939-2012
(also Gold and Hoyle; Pacini & Salvati, Rees & Gunn)

Pulsar Wind Nebulae



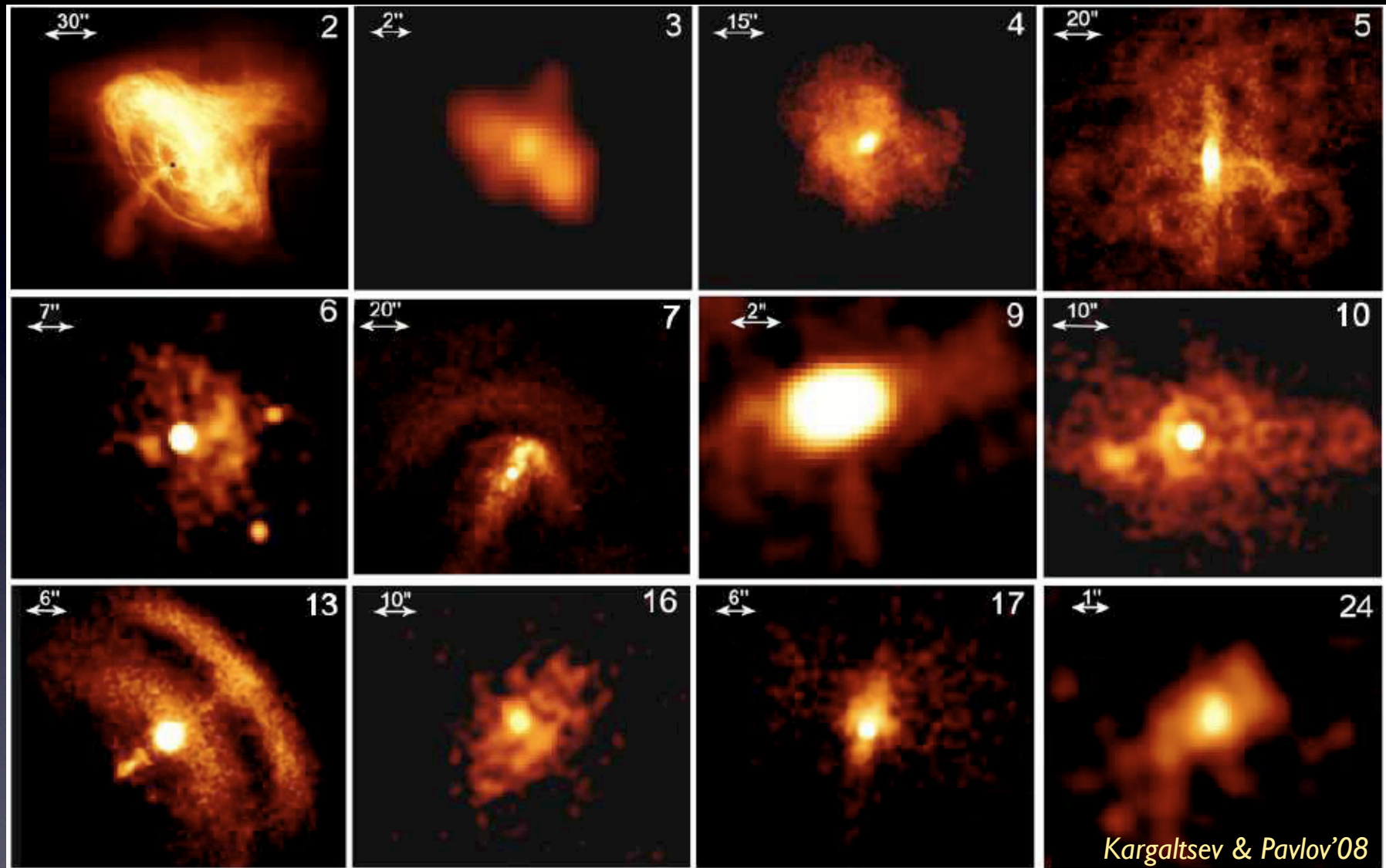
composite



- PWN: **Bubbles of relativistic particles** inflated by pulsar's relativistic wind
 - ✓ Radio to X-rays: synchrotron radiation (X-ray photon index $\sim 1.5-2$; $L_x \ll \dot{E}$).
 - ✓ gamma-rays: IC scattering (synchrotron, CMB, IR, starlight), pion decay (hadronic)
- “**Calorimeters**” for the study of pulsars/Pathfinders for Pulsar Discovery!
- Probes for the **Interaction** of their relativistic winds with the surrounding: SN ejecta (earlier) or ISM (later): PWN **evolution**
- Seed the Galaxy with **energetic particles and magnetic fields**
- Efficient Engines for **Cosmic Ray Acceleration** up to TeV energies

Chandra: New/Sharp Eyes on PWNe

Jet-Torus sample

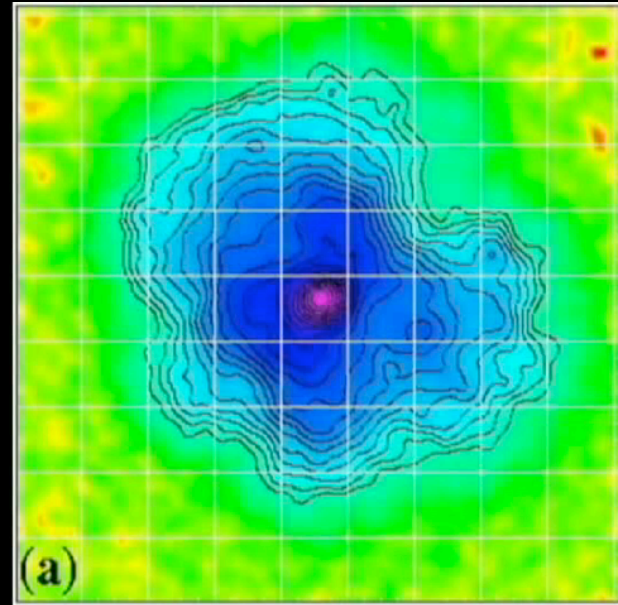


Kargaltsev & Pavlov'08

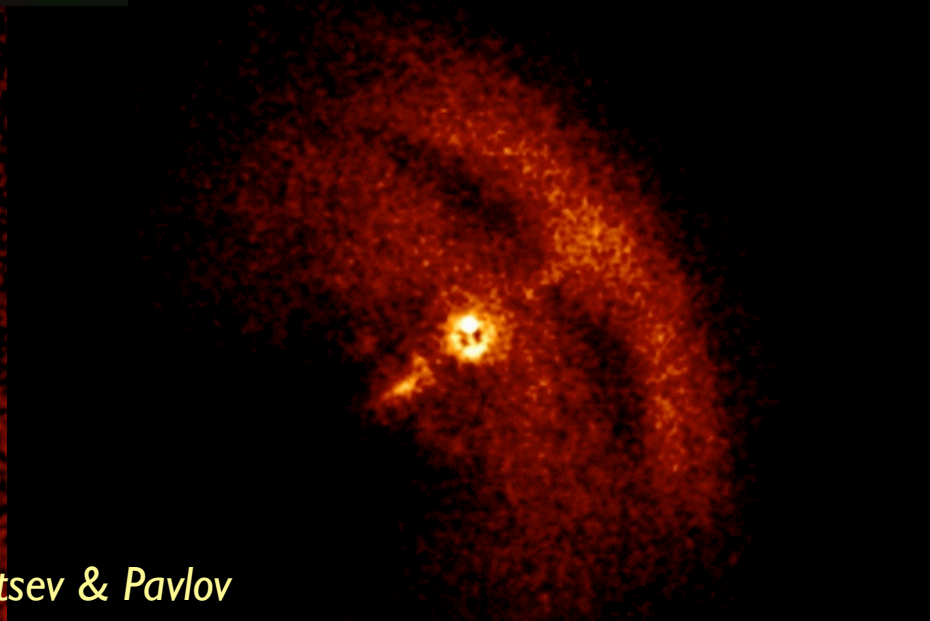
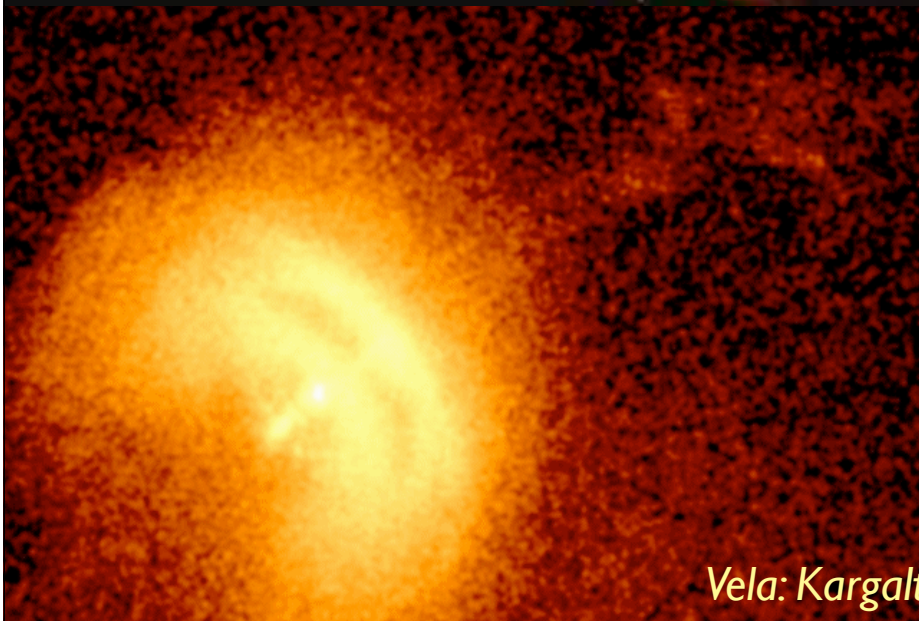
Jets/Torus: Numerical Simulations following the time-dependent evolution
(e.g. *Del Zanna et al.'06*, *Buccianitni et al.'04*; *van der Swaluw et al.'04*; *Blondin, Chevalier, Frieson'01*)

PWN variability (movies)

$v \sim$ fraction of c

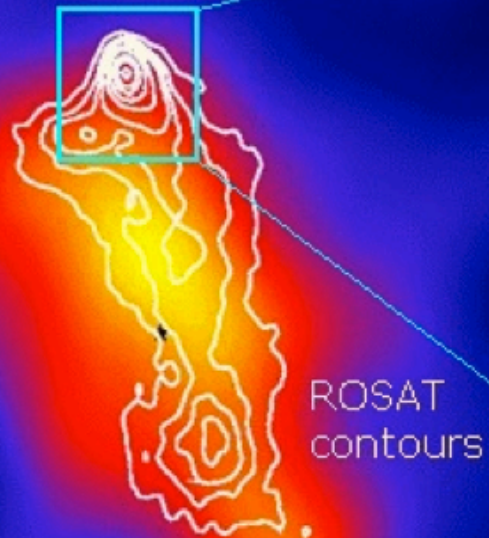


G21.5-0.9: Matheson & Safi-Harb

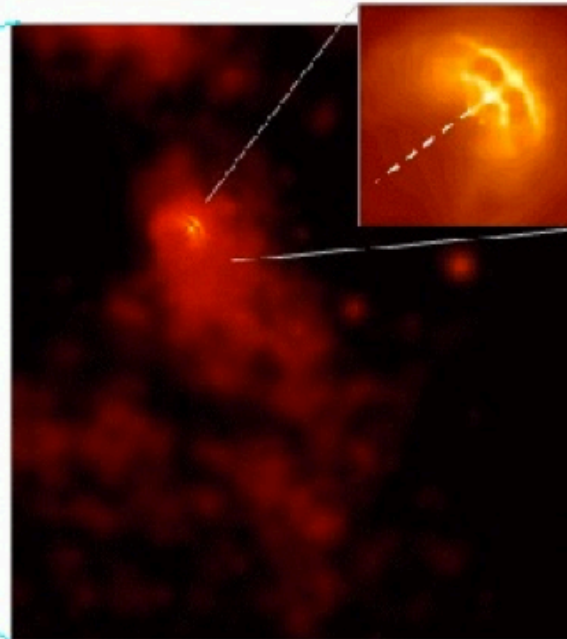


PWN Evolution

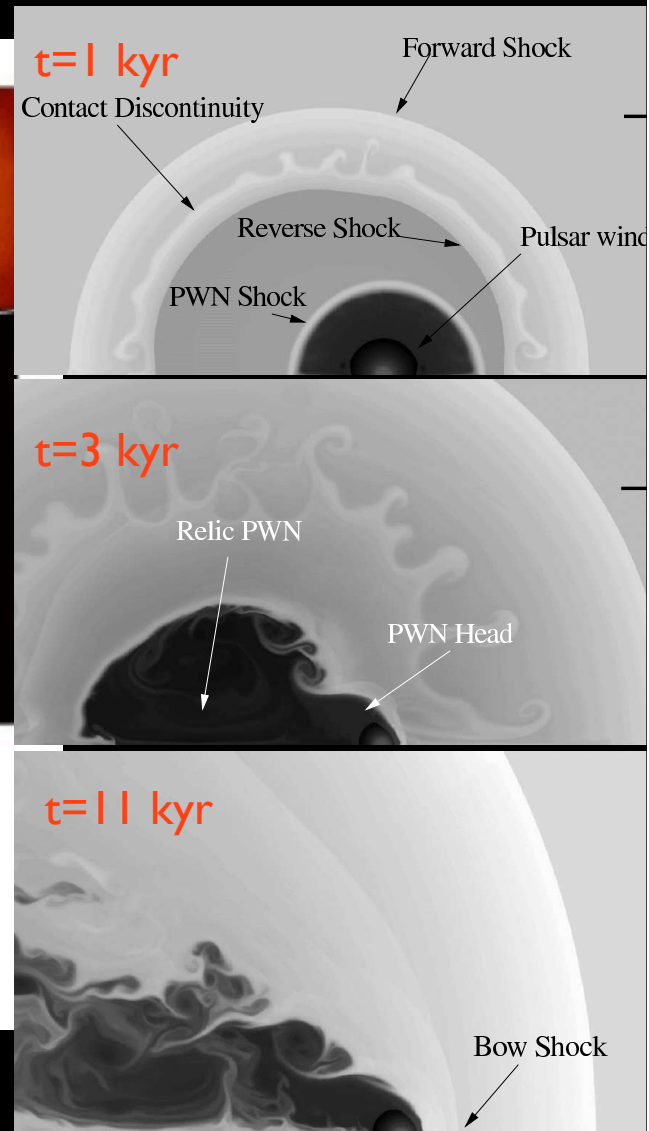
Vela



HESS: Aharonian et al. 2006



Chandra
Pavlov et al. 2003

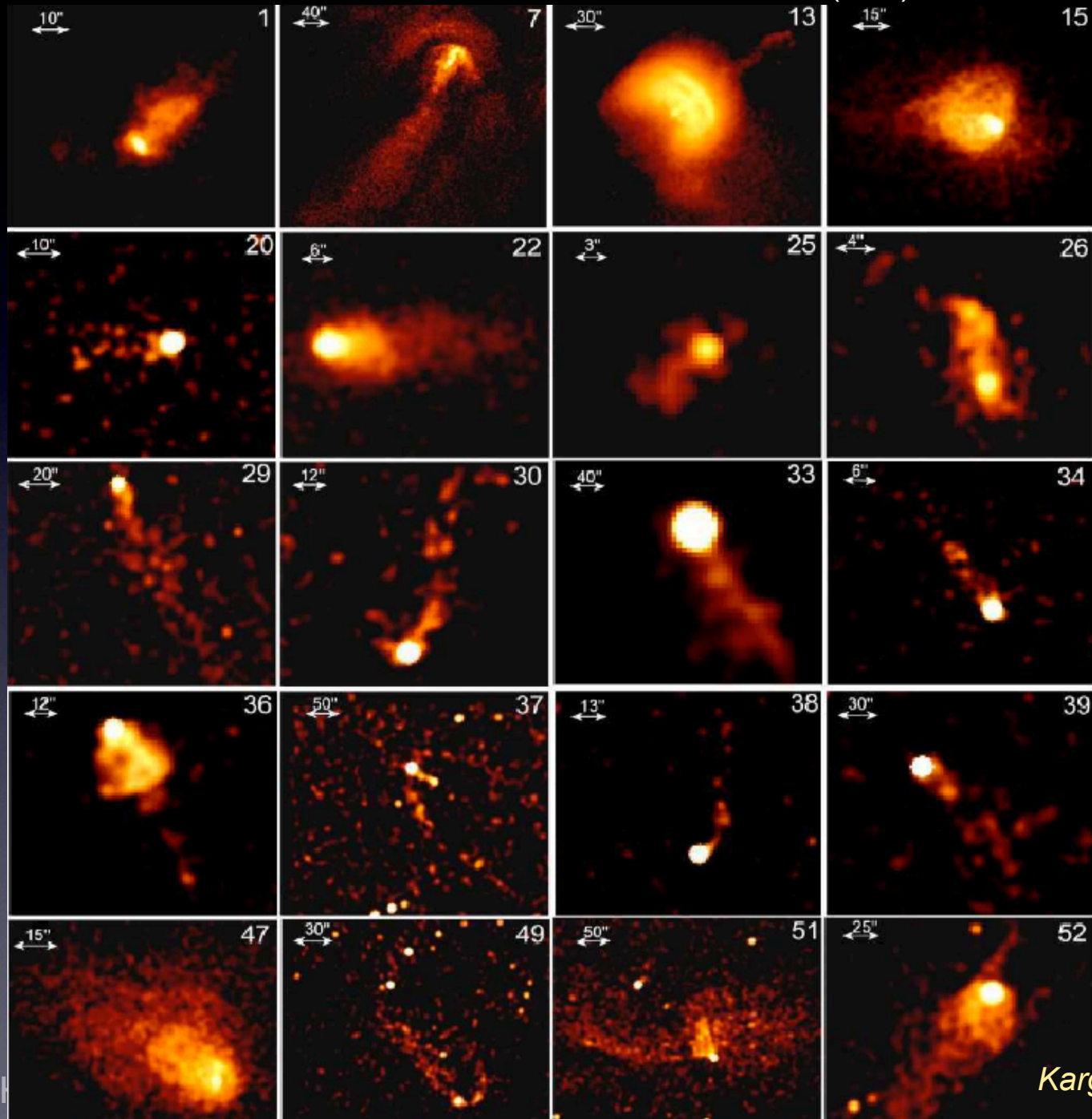


van der swaluw 2004
(also Blondin et al. 2001)

“relic” PWNe
observed in TeV gamma-rays

Bow-Shock PWNe

Ram Pressure Confinement: Bow shock+tail (trail)



Some Statistics

- As of today, we know of **308** Galactic SNRs (274+34; a *new and up-to-date HE SNRcat*, which complements Dave Green's catalogue in radio)
- ~90 SNRs contain PWNe or candidates
 - ✓ ~35 are HESS sources
 - ✓ ~30 **lack shells** (including the Crab): “**naked PWNe**”

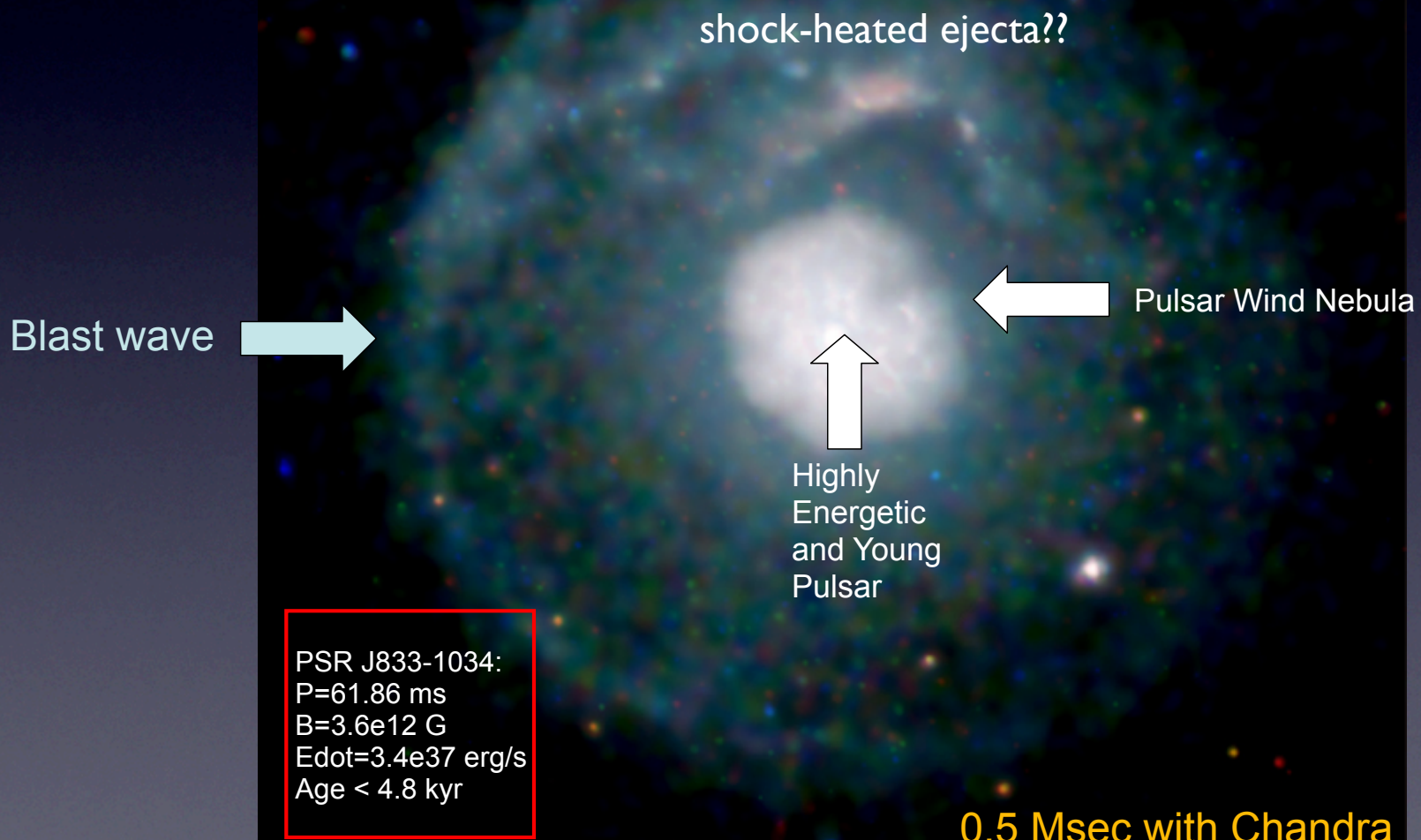


A New High-Energy (X+g) SNRs catalogue:
<http://www.physics.umanitoba.ca/snr/SNRcat>
Ferrand & Safi-Harb 2012, AdvSpRes
being updated with PWN data
(a dedicated, up-to-date, PWN catalogue)

see poster
IAUS291-1-0206

The shell is missing in many (Crab-like) PWNe,
including the Crab itself!

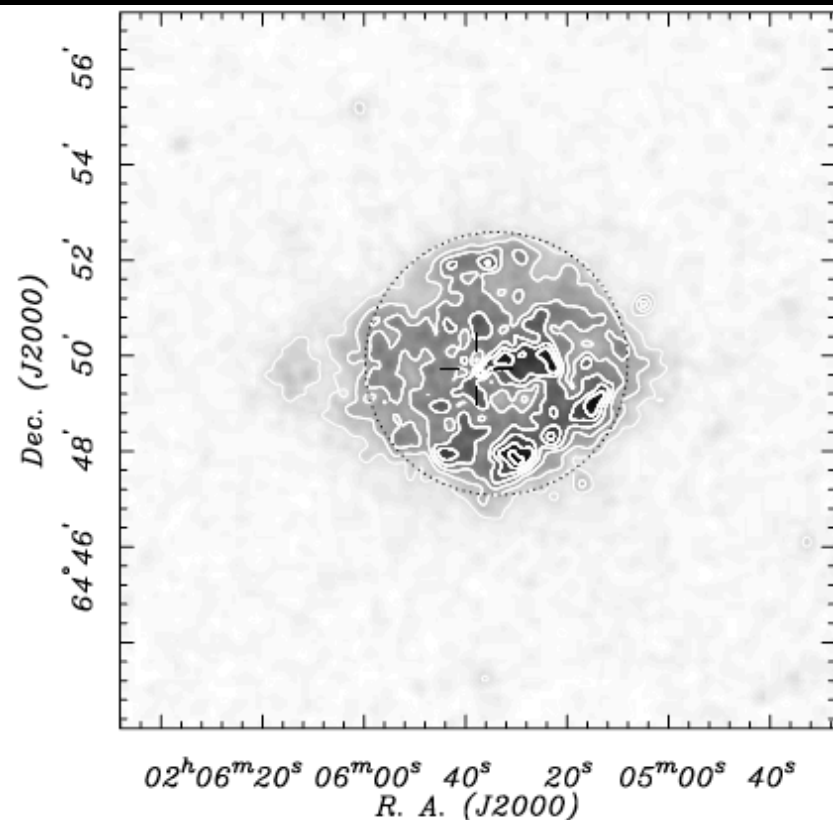
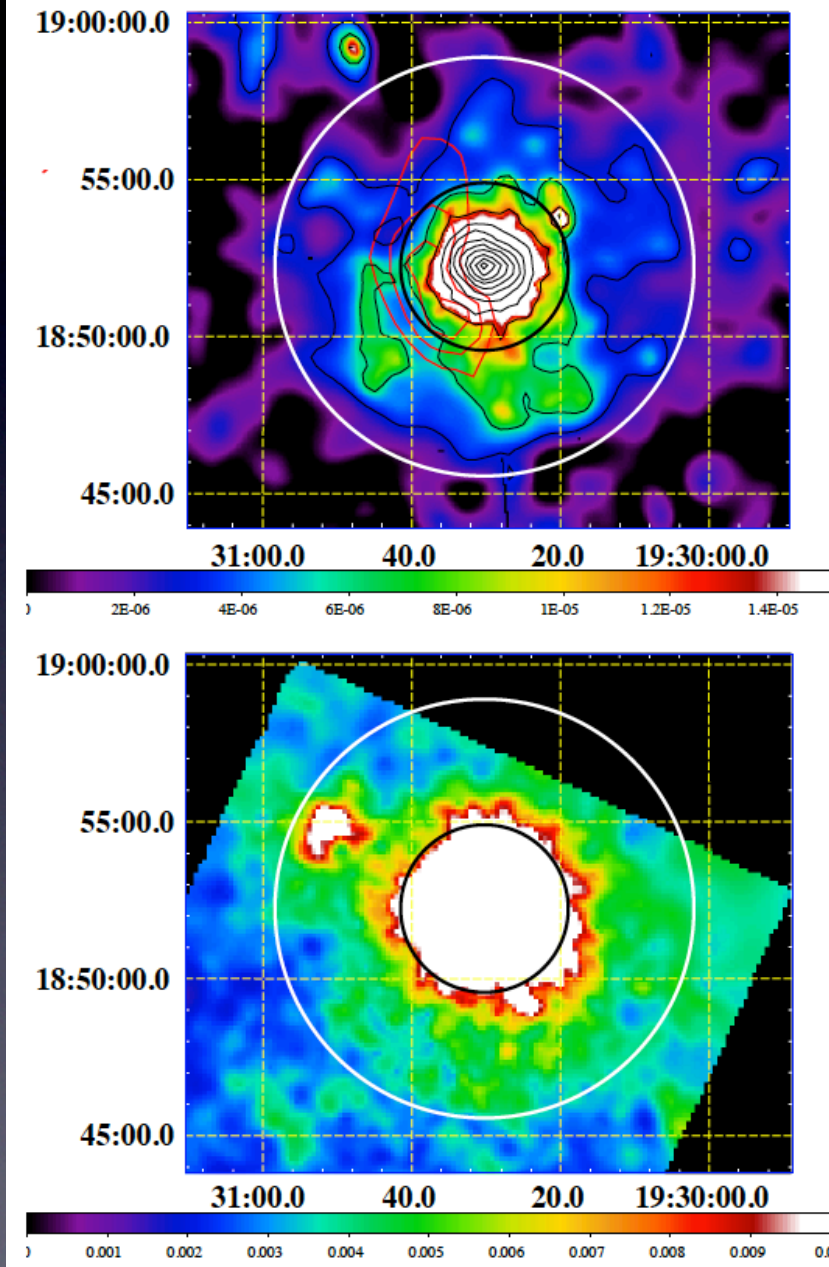
Chandra pinpoints the blast wave in a “Crab”-like PWN



0.5 Msec with Chandra

Matheson & Safi-Harb 2005, 2010

Evidence for X-ray “Shells” around 2 other PWNe

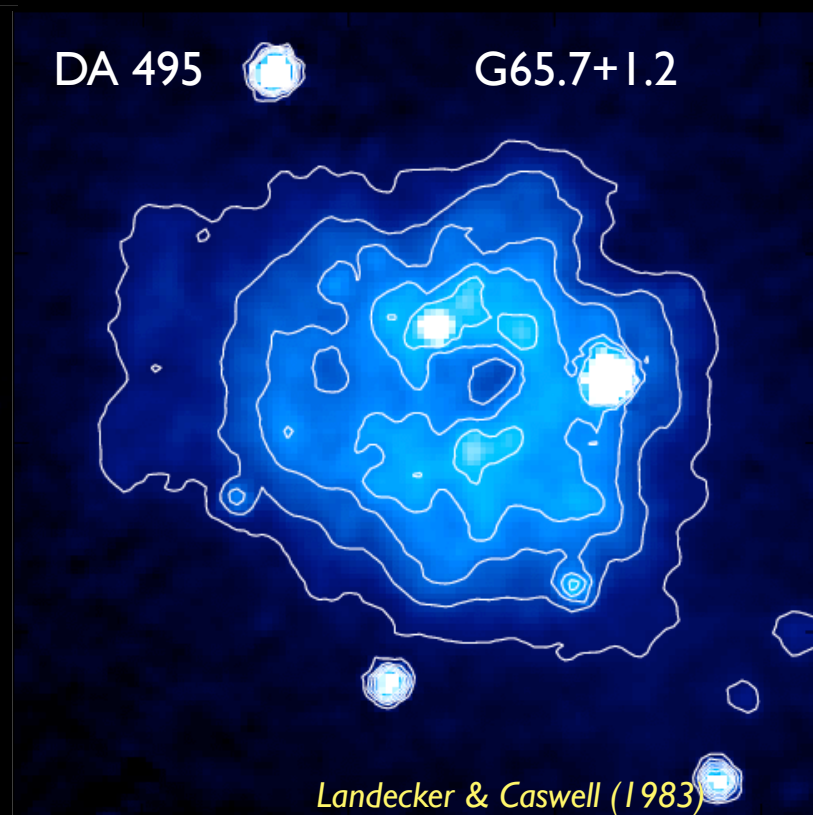
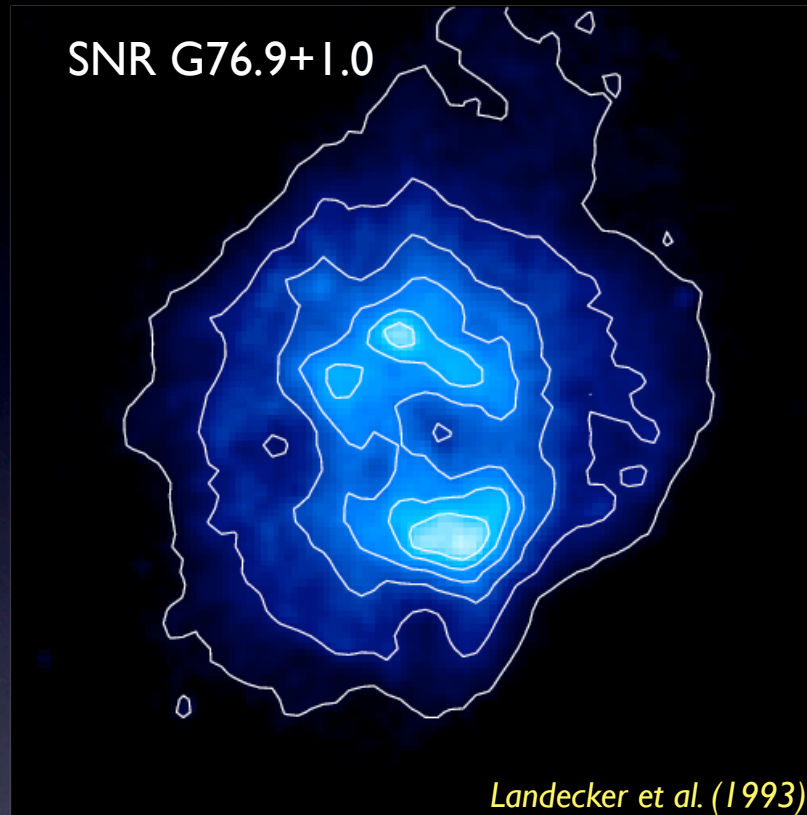


3C58, XMM-Newton
Gotthelf et al. 2007

G54.1+0.3, XMM-Newton and Suzaku
Bocchino et al. 2010

Not-so-Crab-like

Two unusual Radio Nebulae

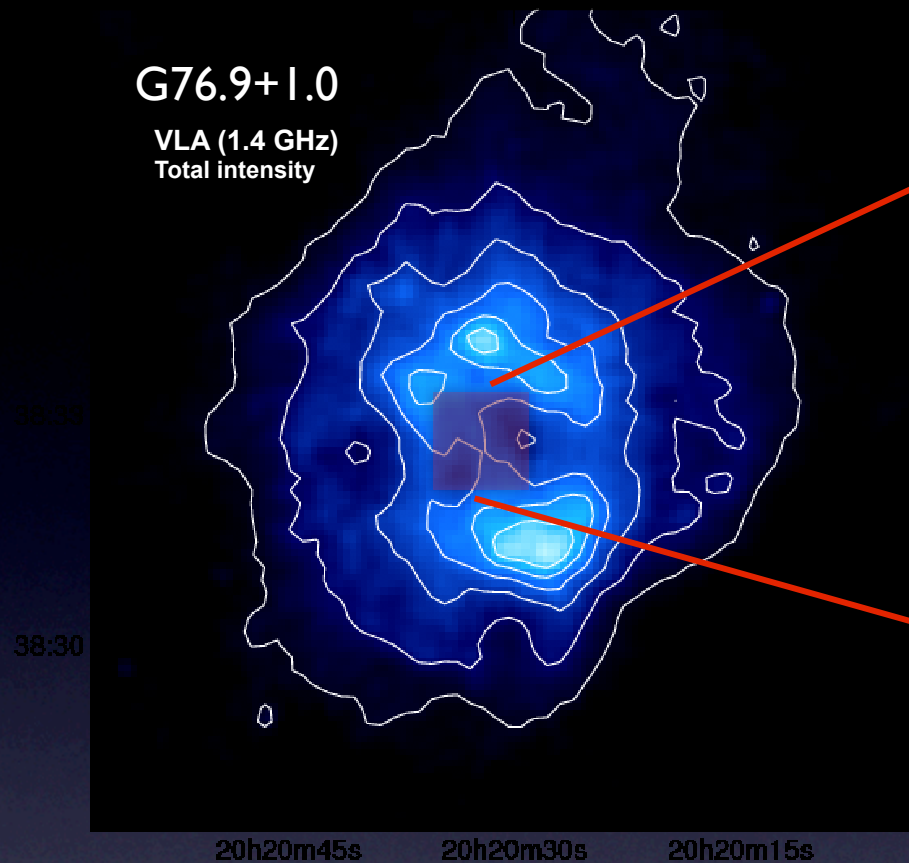


- Roughly annular morphologies with inner/outer radii of $\sim 1'/10'$
- Unlike shell-type SNRs, **not limb-brightened**
 - ✓ their non-thermal flux falls off away from centre, implying a central engine (pulsar)
- **Radio spectrum too steep** for a plerion, $\alpha \approx 0.6$, more typical of shells
- Low-frequency (radio) spectral break
- In polarized emission, **strong axisymmetry** and double-lobed morphology
- See Arzoumanian et al. (2011, 2008).

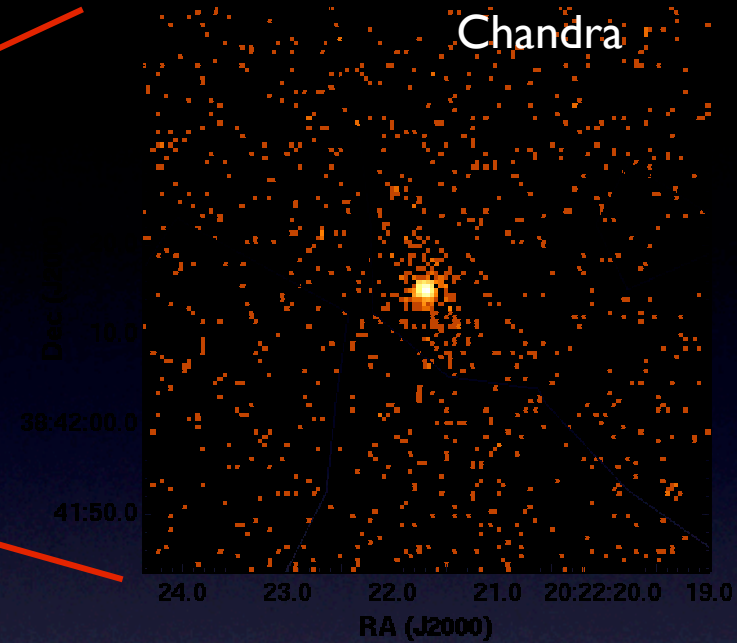
G76.9+1.0

G76.9+1.0

VLA (1.4 GHz)
Total intensity



Chandra

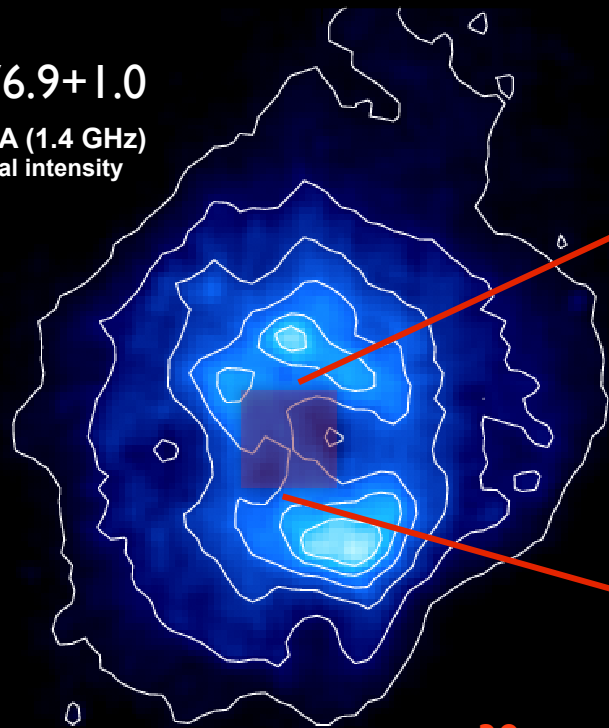


Chandra
pinpoints a “pulsar” candidate

G76.9+1.0

G76.9+1.0

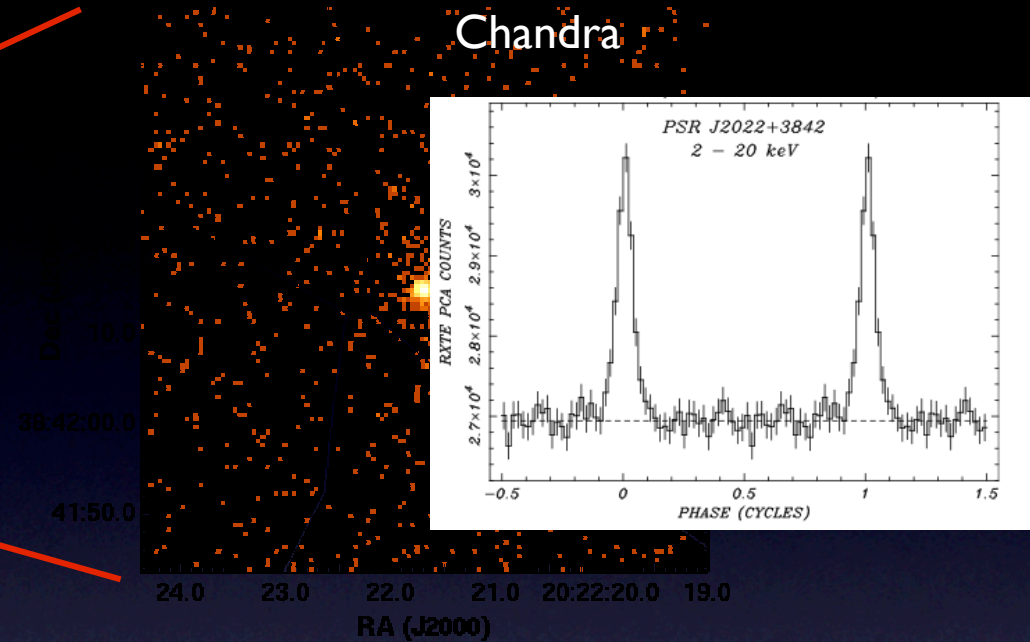
VLA (1.4 GHz)
Total intensity



$\dot{E} = 1.2 \times 10^{38} \text{ erg/s}$

20h20m45s 20h20m30s 20h20m15s

Chandra



Chandra

pinpoints a “pulsar” candidate

Radio and X-ray pulsar searches lead to
the discovery of a very energetic pulsar!
The 2nd most energetic after the Crab pulsar and the fastest
known pulsar in our Galaxy!!



GBT



RXTE

G76.9+1.0

G76.9+1.0

VLA (1.4 GHz)
Total intensity

$$P = 24.3 \text{ ms}$$

$$\dot{P} = 4.2 \times 10^{-14} \text{ s s}^{-1}$$

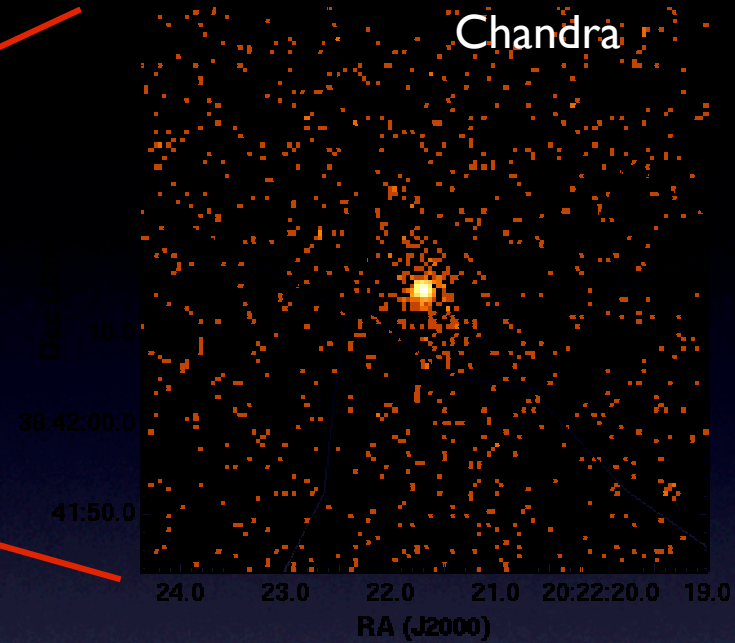
$$\text{DM} = 427 \text{ pc cm}^{-3}$$

$$B \approx 1 \times 10^{12} \text{ G}$$

$$\dot{E} = 1.2 \times 10^{38} \text{ erg/s}$$

20h20m45s 20h20m30s 20h20m15s

Chandra



Chandra
pinpoints a “pulsar” candidate

G76.9+1.0

G76.9+1.0

VLA (1.4 GHz)
Total intensity

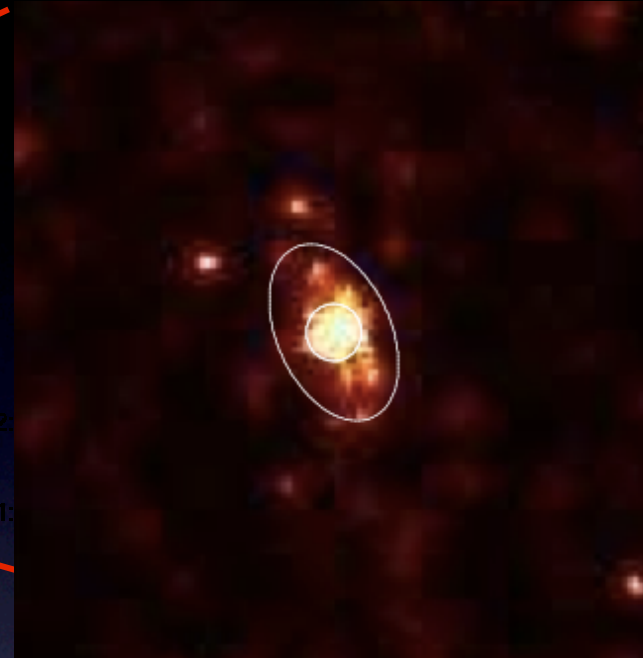
$$P = 24.3 \text{ ms}$$

$$\dot{P} = 4.2 \times 10^{-14} \text{ s s}^{-1}$$

$$\text{DM} = 427 \text{ pc cm}^{-3}$$

$$B \approx 1 \times 10^{12} \text{ G}$$

$$\text{Edot} = 1.2 \times 10^{38} \text{ erg/s}$$



Chandra

pinpoints a “pulsar” candidate

Spectral fits (Chandra)		
Component	Nebula	PSRJ2022
Model	Power Law	Power Law
Γ	1.4	1.0 ± 0.2
n_H (10^{22} cm^{-2})	$(1.6 \pm 0.3) \times 10^{22} \text{ cm}^{-2}$	
Flux (abs 2–10 keV; $\text{ergs cm}^{-2} \text{ s}^{-1}$)	4×10^{-14}	5.3×10^{-13}
Lx (2–10 keV)	5.6×10^{32}	7×10^{33}

- Very hard X-ray spectrum
- Unusually low L_x/Edot ($6e-5$)
- PWN appears “old”
- PSR appears “young”

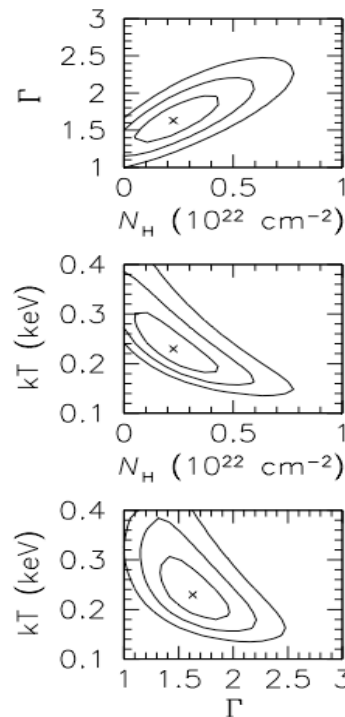
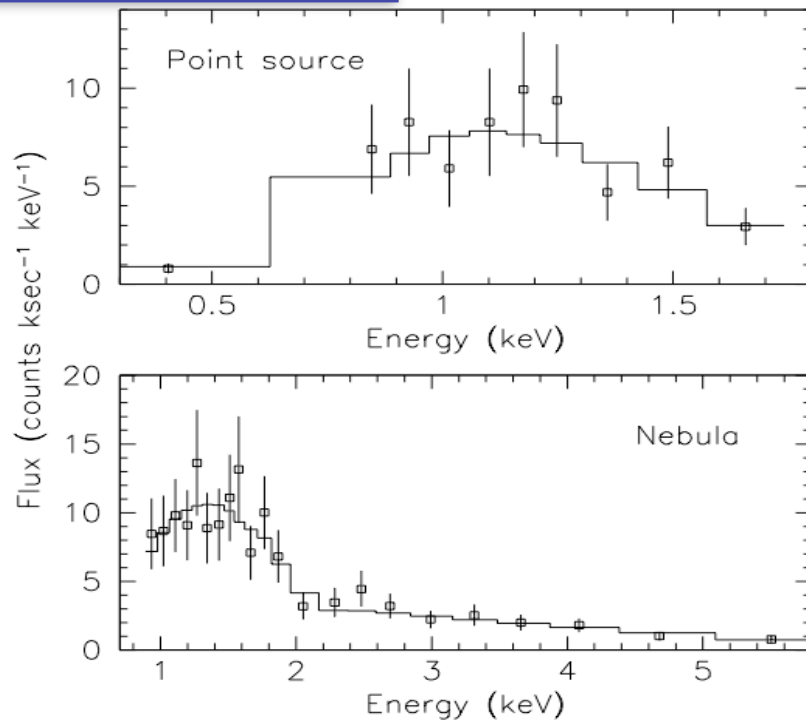
$D \approx 1$ kpc

Age ≈ 20 kyr

$R_{\text{PWN radio}} \approx 6.4 \times 10^{18}$ cm

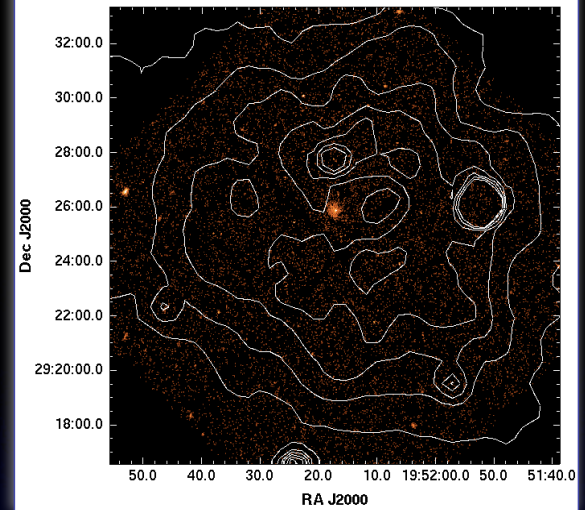
$R_{\text{PWN X-ray}} \approx 2.4 \times 10^{17}$ cm

G65.7+1.2



Spectral fits (Chandra)

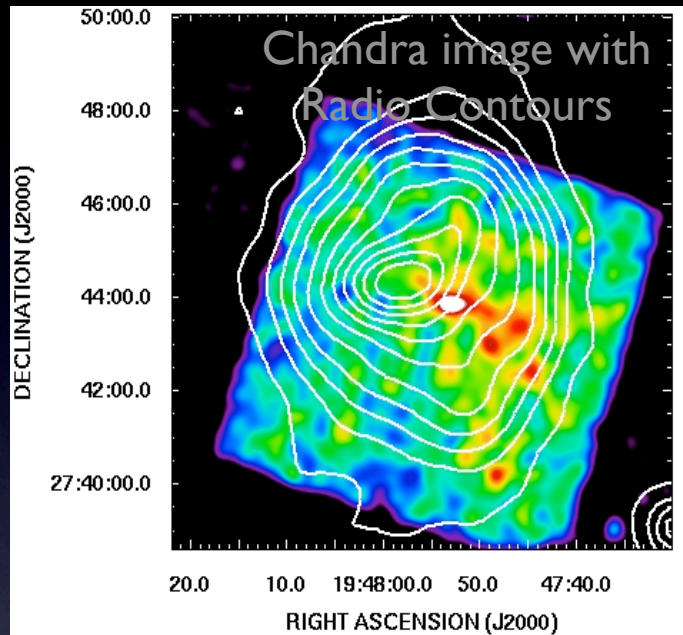
Component	Nebula	Pt srce
Model	Power Law	Blackbody
Γ / kT_{eff} (MK)	1.6	2.5
n_{H} (10^{22} cm^{-2})	< 0.4	
Flux (unabs 0.5–10 keV; ergs $\text{cm}^{-2} \text{ s}^{-1}$)	1.7×10^{-13}	8×10^{-14}
Lx (0.5-10 keV)	3.3×10^{31}	$\sim 10^{31}$



- Spectral and energetic modelling suggest **20 kyr** age and strong, ~ 1 mG, PWN field.
- Implied spin-down luminosity: $\sim 10^{35}$ ergs/s
- No pulsations in Arecibo and XMM-Newton searches.

Arzoumanian, SSH, et al. 2004 & 2008
Kothes, Landecker, Reich, SSH, Arzoumanian 2008

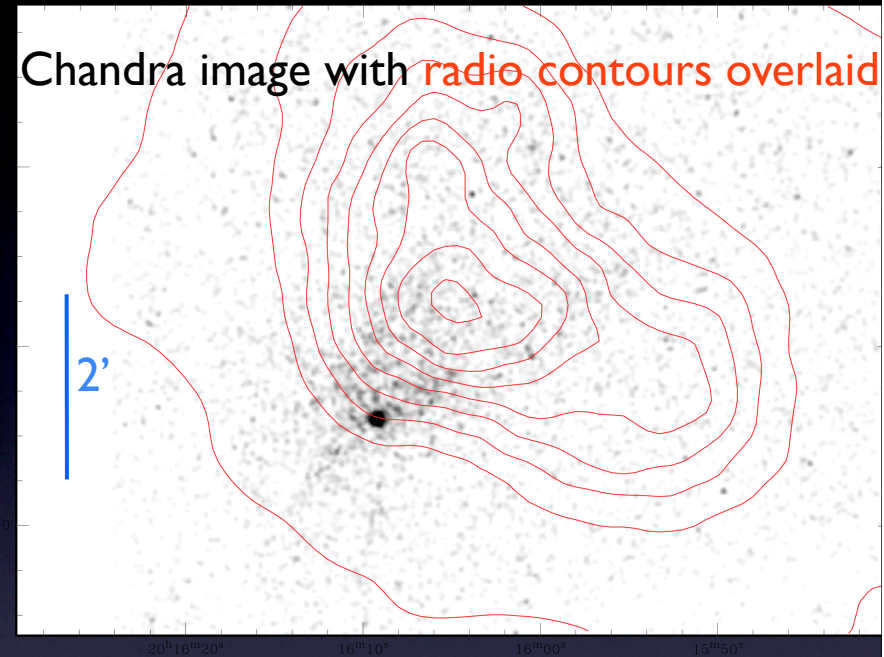
Another two non-Crab like radio nebulae



- steep central component ($\alpha \sim 0.4-0.5$)
- Low-freq. spectral break
- Large, implying evolved?

G63.7+1.1: A PWN interacting with a molecular cloud??

- $N_H = 1.6 (1.0 - 2.2) \times 10^{22} \text{ cm}^{-2}$
- $\Gamma = 1.7 (1.4 - 2.1)$
- X-ray flux = $2.7 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$
- $L_x (6 \text{ kpc}) = 1.6 \times 10^{33} \text{ erg s}^{-1}$



G74.9+1.2: A Relic/Evolved PWN

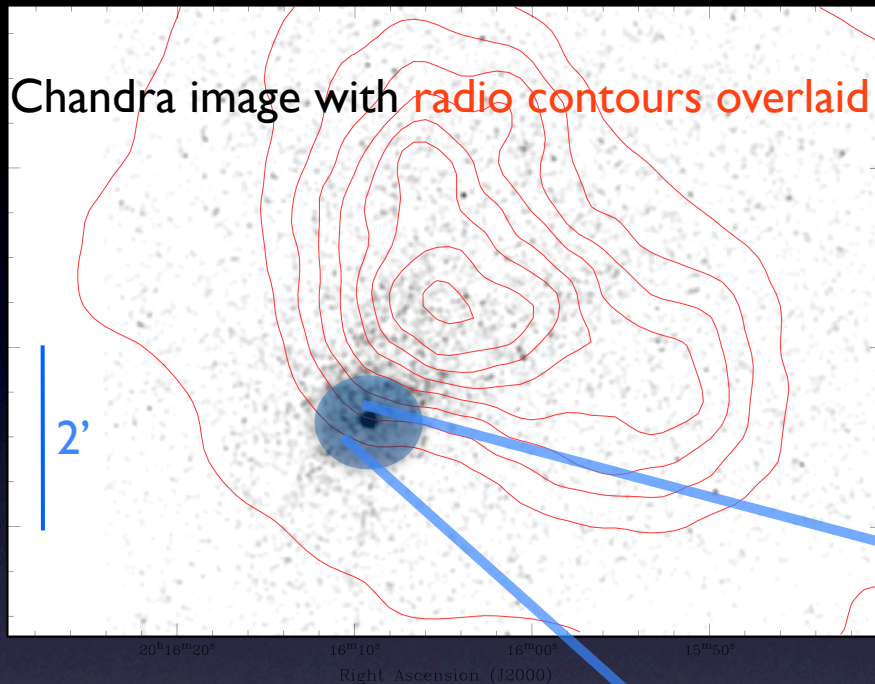
- $N_H = 1.38 (1.21-1.57) \times 10^{22} \text{ cm}^{-2}$
- $\Gamma = 1.7 (1.5-1.8)$
- ✓ steepens away from point source
- $L_x (6.1 \text{ kpc}) \sim 1.5 \times 10^{34} \text{ erg/s (nebula)}$

Chandra (and XMM) reveal low-luminosity and “offset” X-ray nebulae

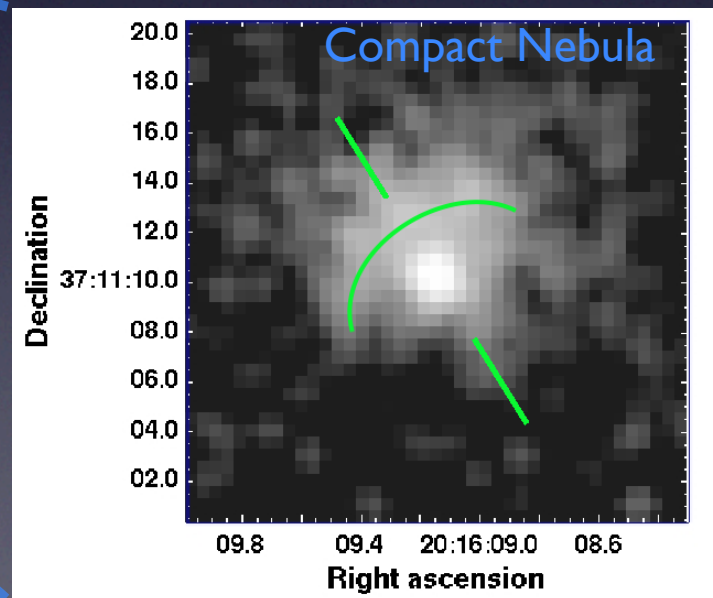
SSH and H. Matheson
in collaboration with Roland Kothes

G74.9+1.2

Chandra reveals a compact and an extended “offset” PWN

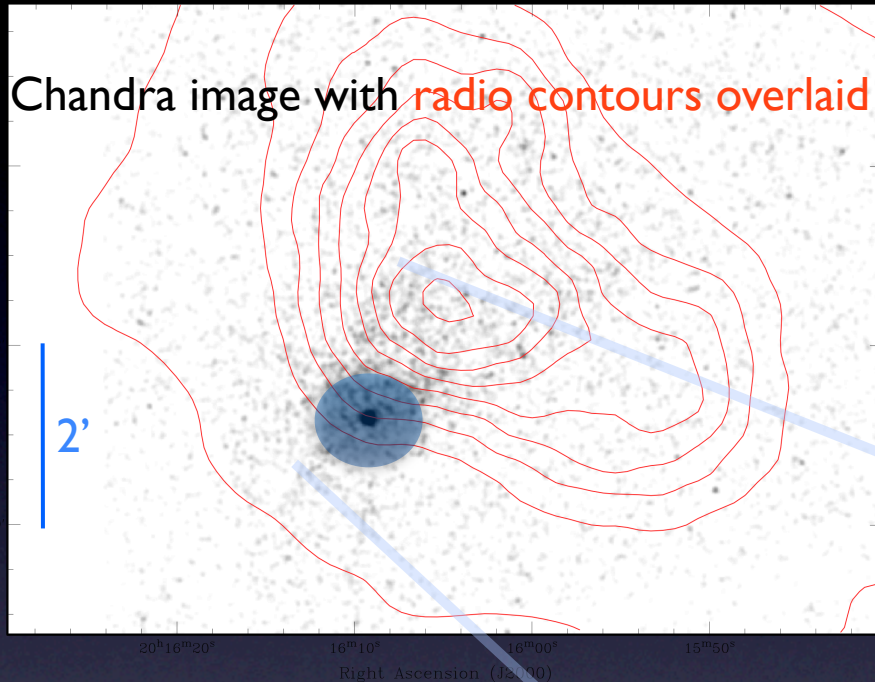


- Plerion (radio)
- 8'x6' size in the radio (**red contours**)
- Low-frequency spectral break, no pulsar
- New sensitive radio studies:
 - ✓ a larger size of ~16': a linear size of ~28 pc (at 6.1 kpc) and indicating a **highly evolved SNR**
 - ✓ Unusually steep spectral index, $\alpha \approx 0.48$ (for the central cpt) and a harder component outward



G74.9+1.2

Chandra reveals a compact and an extended “offset” PWN



- Plerion (radio)
- 8'x6' size in the radio (**red contours**)
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Nebula: **cometary morphology**

- ✓ neutron star (candidate) moving to the south-east?
Offset of ~2' requires a speed of ~175 (km/s)/ τ_{20}

✓ **Crushed/relic PWN** as e.g. in Vela-X, G327.1-1.1.

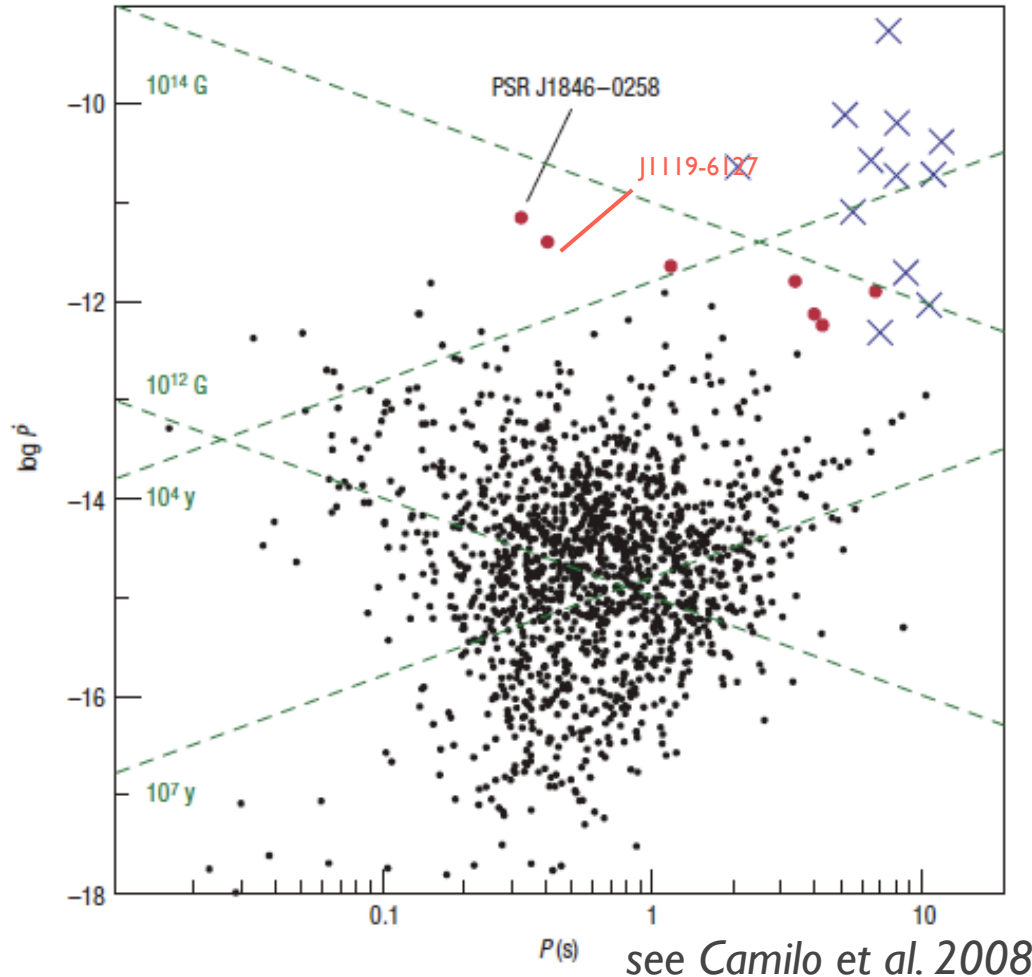
- ▶ Offset between R, X; steep central radio spectrum
- ▶ Bridge connecting them.
- ▶ Gamma-ray detection (*Aliu et al*).



High-B Pulsars (HBPs) in SNRs

$$\sim 10^{13} < B \text{ (Gauss)} < \sim 10^{14}$$

PSR J1846-0258
in SNR Kes75
 $P = 0.3 \text{ s}$
 $B = 5 \times 10^{13} \text{ G}$
($> B_{\text{QED}}$)
 $\dot{E} = 8.3 \times 10^{36} \text{ erg/s}$
Age $\sim 725 \text{ years}$



PSR J1119-6127 in SNR
G292.2-0.5

$P = 408 \text{ ms}$

$B = 4.1 \times 10^{13} \text{ Gauss} \sim B_{\text{QED}}$

$\dot{E} = 2.3 \times 10^{36} \text{ erg/s}$

Age $\sim 1900 \text{ yrs}$

Do HBPs power nebulae?

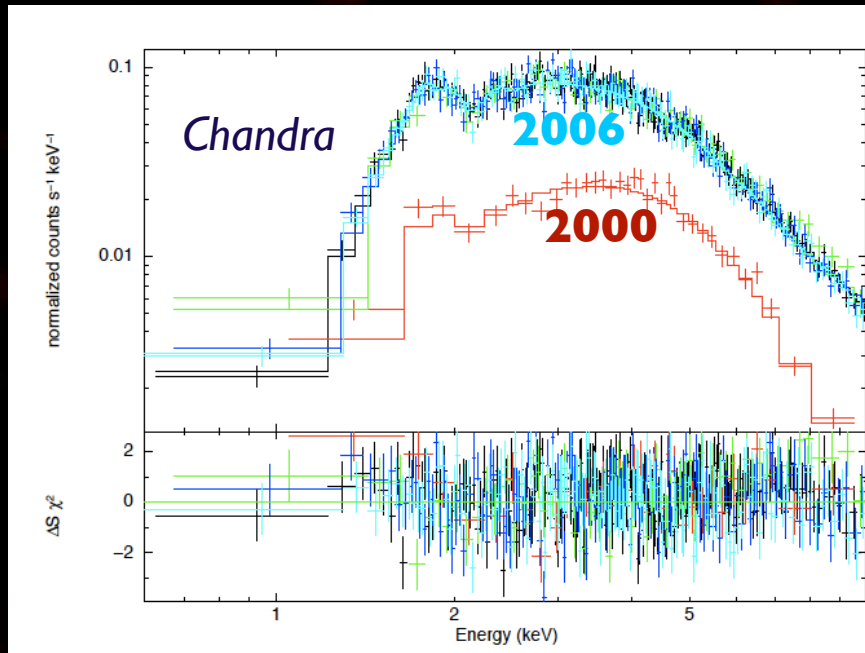
J1846-0258 in SNR Kes75

($B=5e13$ Gauss, $\dot{E}=8.3e36$ erg/s, Age ~ 725 yrs)
powered by both rotation and magnetism



J1846-0258 in SNR Kes75

($B=5e13$ Gauss, $\dot{E}=8.3e36$ erg/s, Age ~ 725 yrs)
powered by both rotation and magnetism



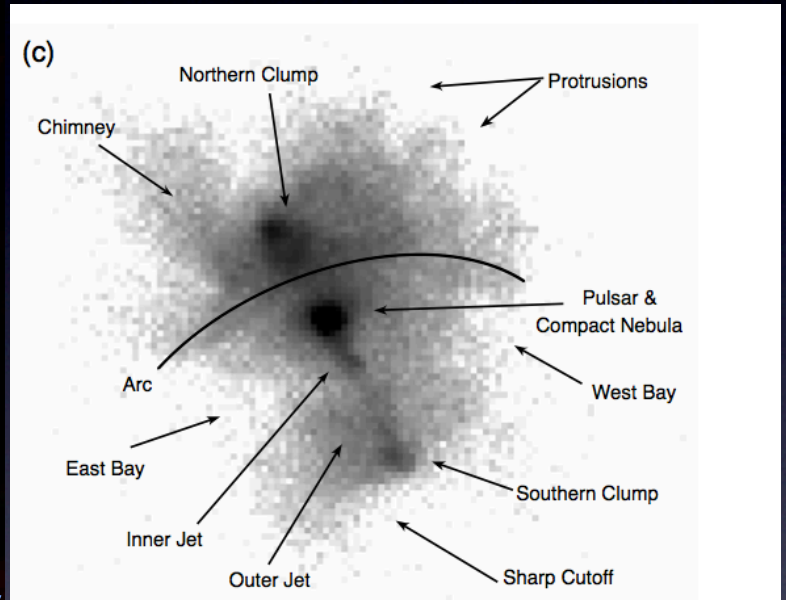
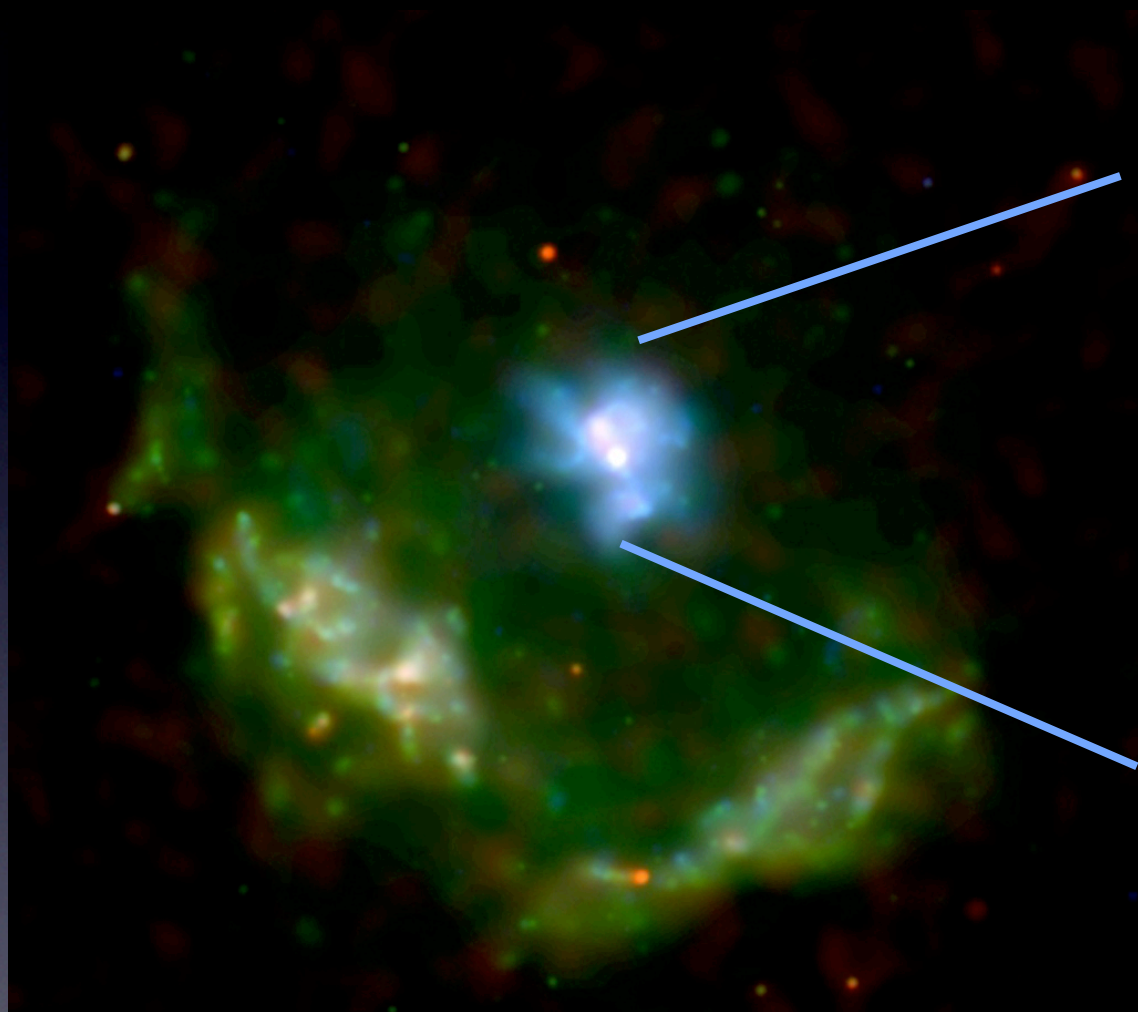
Kumar & SSH 2008

(also Gavril et al. 2008)

J1846-0258 in SNR Kes75

($B=5e13$ Gauss, $\dot{E}=8.3e36$ erg/s, Age ~ 725 yrs)

powered by both rotation and magnetism



Ng et al. 2008

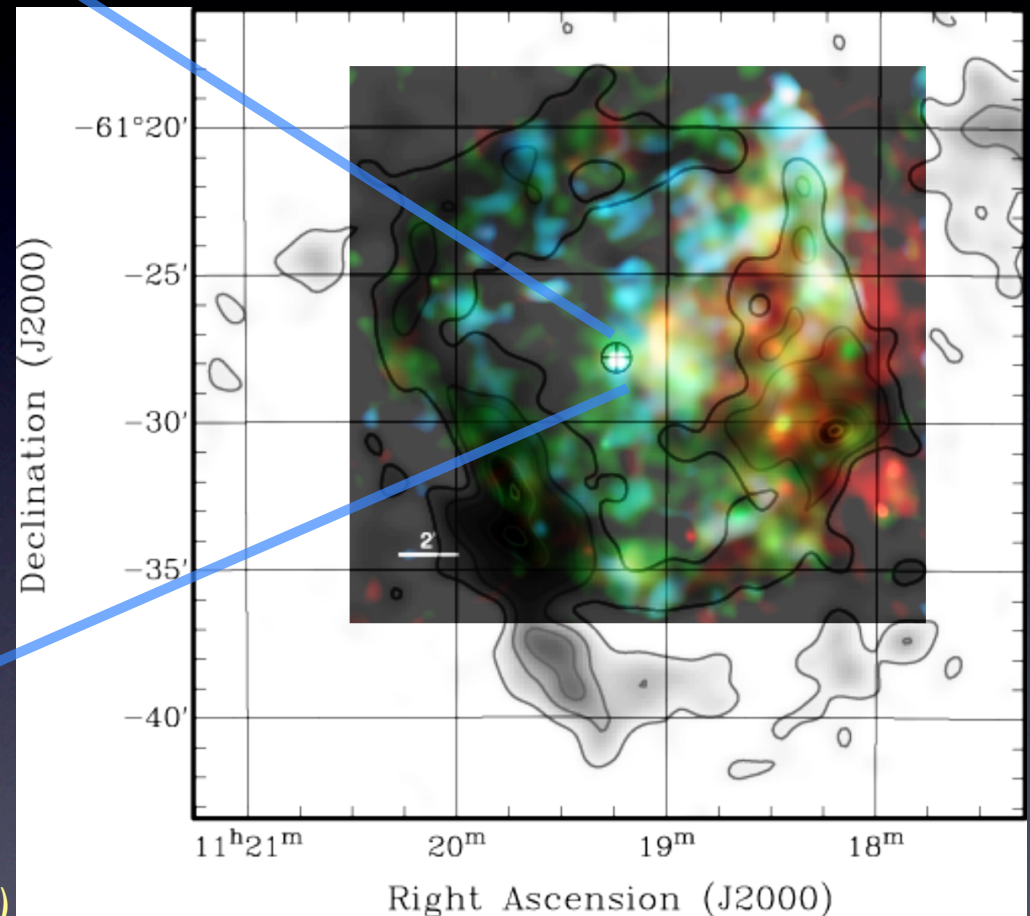
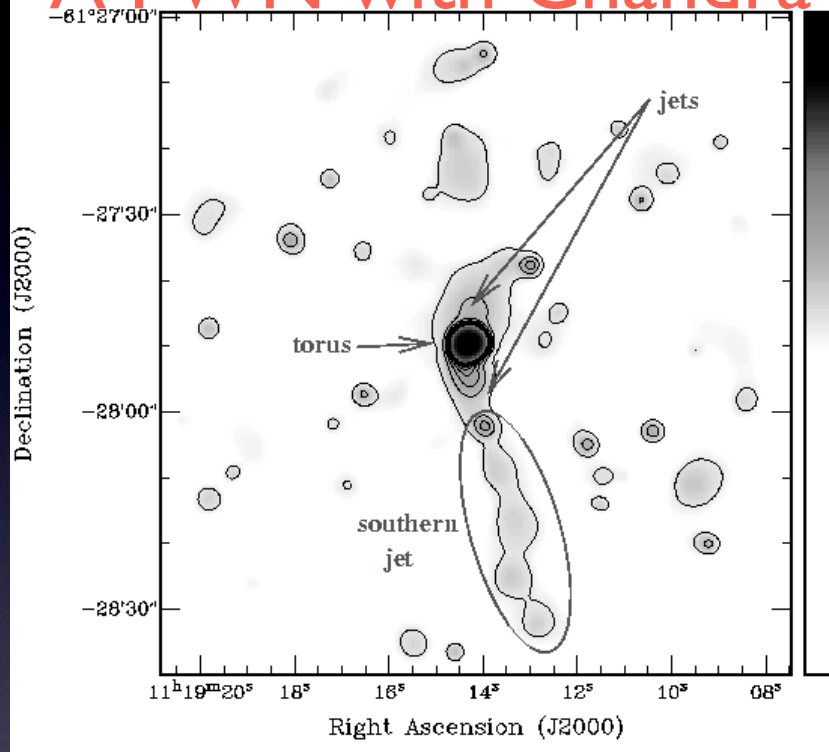
high $L_x/\dot{E} \sim 0.2-0.3$
magnetically powered?

Variability in the PWN following magnetar-like
bursting activity (Kumar & SSH 2008; Gavril et al. 2008; Ng et al. 2008)

J1119-6127 in SNR G292.2-0.5

($B=4.1 \times 10^{13}$ Gauss, $\dot{E}=2.3 \times 10^{36}$ erg/s, Age $\sim 1,900$ yrs)

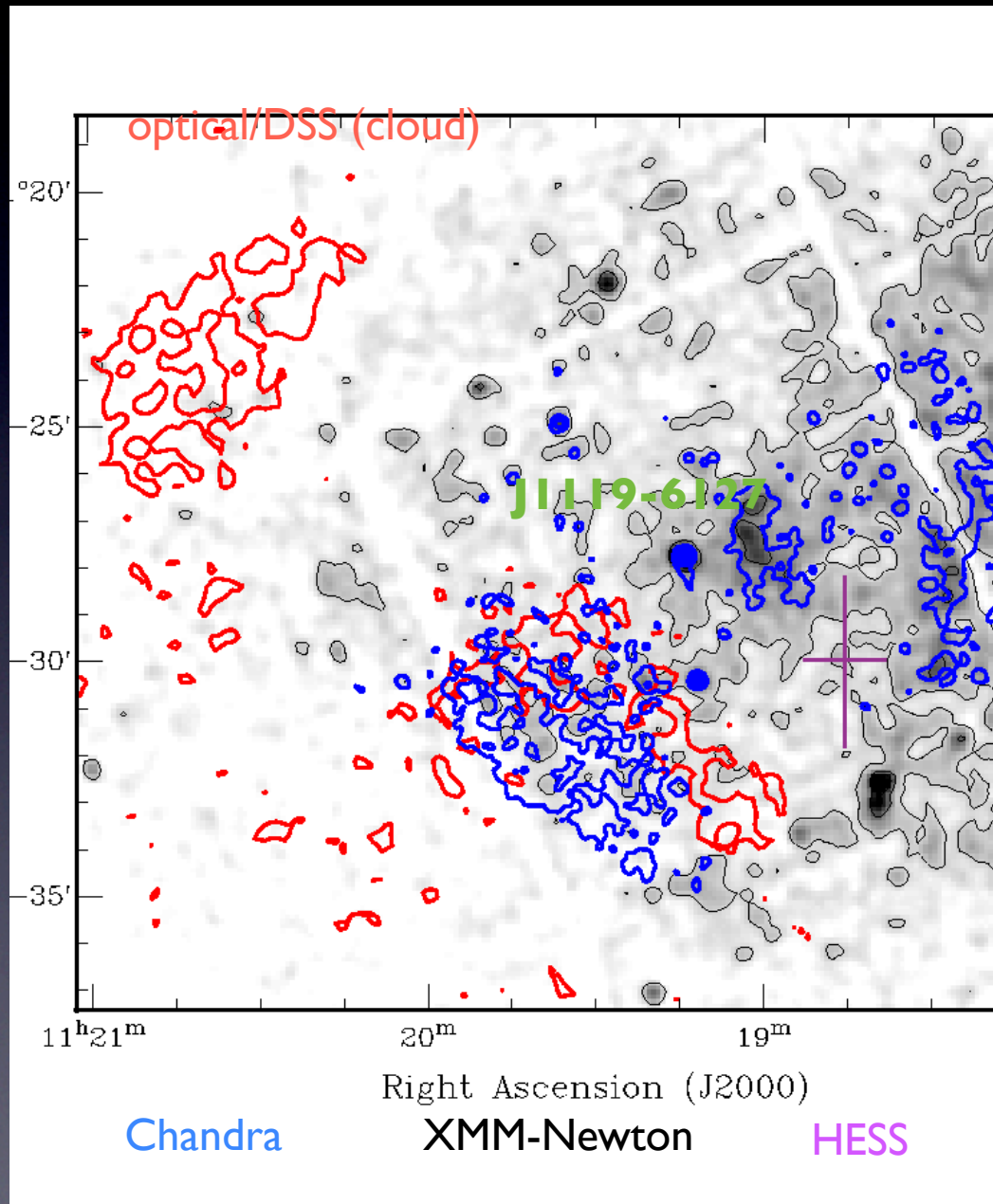
A PWN with Chandra



- X-ray counterpart to PSR J1119-6127 (*Gonzalez & SSH 2003*)
- High pulsed fraction in soft X-ray (*Gonzalez+05*)
- Compact PWN, Southern Jet
- Power law with a hard photon index
- Energetics can be explained by pulsar's $\dot{E}$ (*SSH & Kumar 2008*)

XMM-Newton Energy Image with radio contours (*Caswell et al.*) overlaid
Kumar, SSH & Gonzalez 2012, ApJ

J1119-6127 in SNR G292.2-0.5 multi-wavelength view



Kumar, SSH & Gonzalez 2012, *ApJ*
see poster **IAUS291-0255**

PWNe around other highly magnetized pulsars

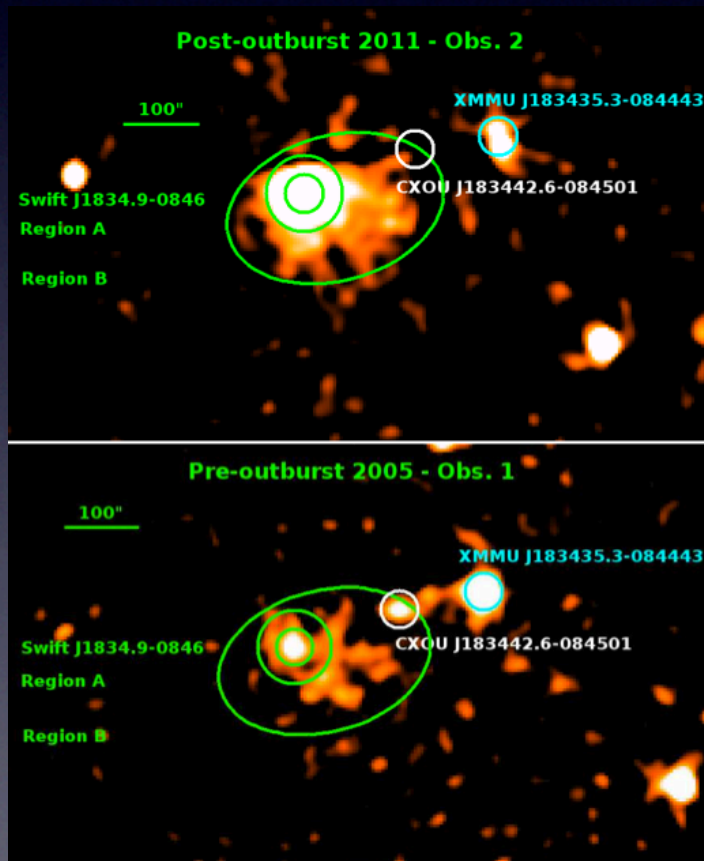
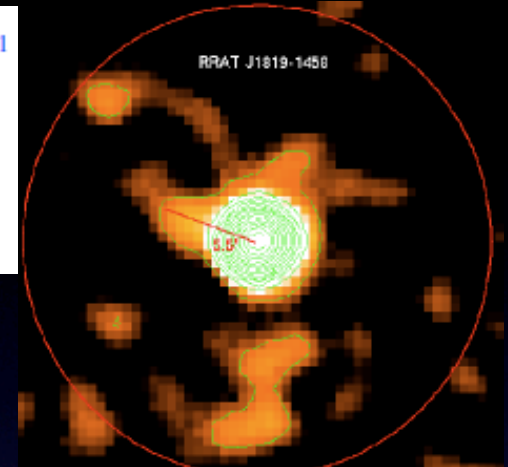
THE ASTROPHYSICAL JOURNAL, 703:L41–L45, 2009 September 20
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doi:10.1088/0004-637X/703/1/L41

DISCOVERY OF EXTENDED X-RAY EMISSION AROUND THE HIGHLY MAGNETIC RRAT J1819–1458

N. REA^{1,2}, M. A. McLAUGHLIN^{3,4,11}, B. M. GAENSLER⁵, P. O. SLANE⁶, L. STELLA⁷, S. P. REYNOLDS⁸, M. BURGAY⁹,
G. L. ISRAEL⁷, A. POSSENTI⁹, AND S. CHATTERJEE¹⁰

see talk later this session by *Ascension Camero et al*



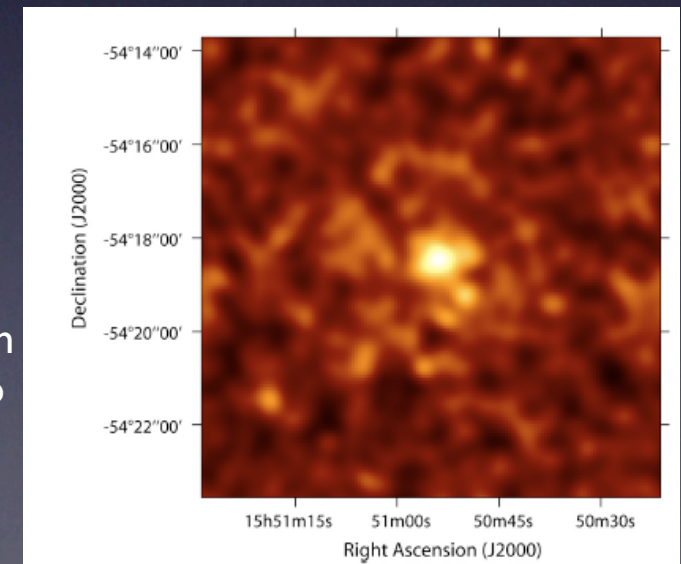
DRAFT VERSION JULY 30, 2012
Preprint typeset using L^AT_EX style emulateapj v. 5/2/11

see talk in *IAUS290*
Friday morning

XMM-Newton VIEW OF Swift J1834.9–0846 AND ITS MAGNETAR WIND NEBULA

G. YOUNES^{1,2}, C. KOUVELIOTOU^{3,2}, O. KARGALTSEV⁴, G. G. PAVLOV^{5,6}, E. GÖĞÜŞ⁷, AND S. WACHTER⁸

IE 1547.0–5408's extended emission, claimed to be a PWN (*Bamba and Vink 2009*): variable, strongly correlated with AXP's flux: Dust Scattering Halo (*Olausen et al. 2011*)

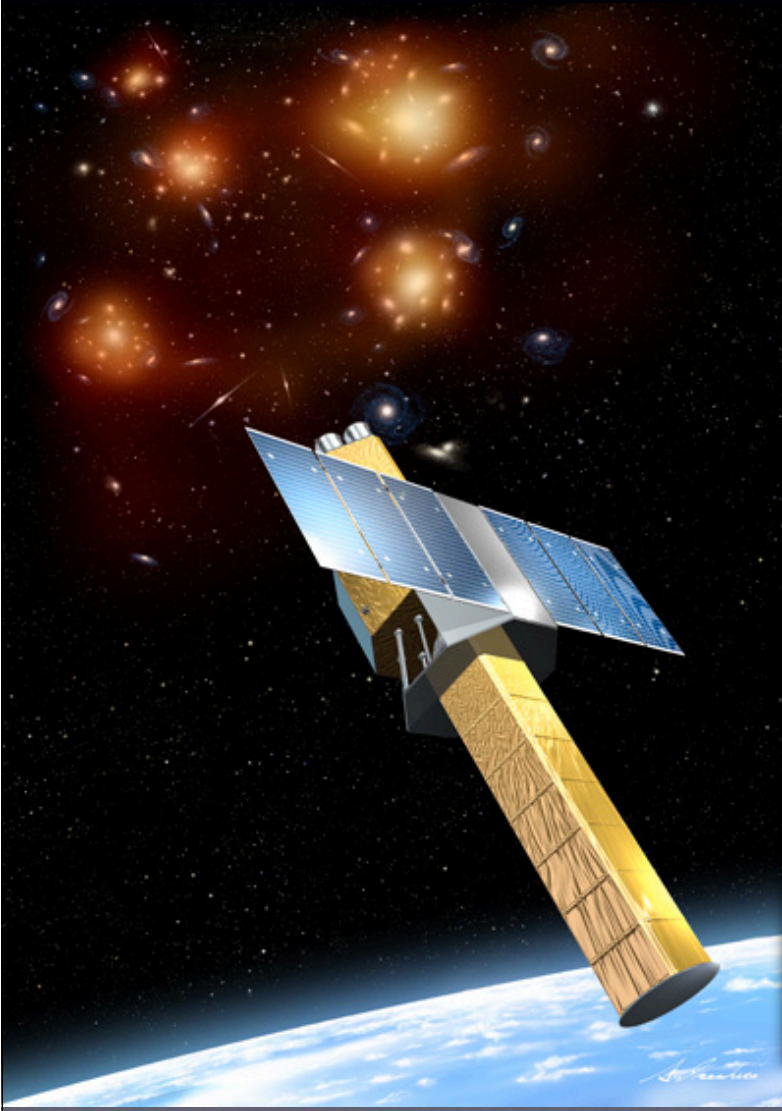


X-ray PWNe around high-B NS

(6 HBPs + 1 RRAT, ~23 magnetars)

PSR	$B_{s,d}$ (10^{13} G)	$\dot{E}$	PWN extent	Photon index	$L_x/\dot{E}$	Comment	Reference
J1119-6127 (see poster 0255, SSH&Kumar)	4.1	$2.30E+36$	6"x15" 20" jet	$1.1^{+0.9}_{-0.7}$ $1.4^{+0.8}_{-0.9}$	$5.00E-04$	properties similar to RPP's PWNe ($L_x/\dot{E} \sim 1e-6-1e-2$, $\gamma \sim 1-2.5$)	Gonzalez & SSH 2003 SSH & Kumar 2008
J1846-0258 Crab+magnetar-like (see poster 0228 by Konar)	5	$8.30E+36$	~40"	~1.9 (1.7-2.2)	~0.2-0.3	variable	Kumar & SSH 2008 Ng et al. 2008
RRAT1819-1458 (see talk by Camero)	5	$3.00E+32$	13"	3.0 ± 1.5	~0.2	see talk (next)	Rea et al. 2009
Swift J1834.9-0846 MVN?	14	$2.10E+34$	70"-150"	3.5 ± 0.6	~0.7	properties similar to RRAT's PWN	Younes et al. 2012
TE 1547.0-5408	22	$1.00E+35$	45" (2.9")	~3.5	0.01	most likely dust scattering halo	Bamba & Vink 09 Olausen et al. 2011

Whether PWNe are powered by rotation and/or magnetism, and are associated with other high-B pulsars is still an open question..



- **Soft X-ray Spectroscopic system**
(SXS, 0.3-12 keV, 3' FOV, ~5eV resolution)
- **Soft X-ray Imaging system**
(0.3-12 keV, 38' FOV)
- **Hard X-ray Imager**
(5-80 keV, 9' FOV, 1.7')
(comparable to NuSTAR)
- **Soft Gamma-Ray Detector**
(50-600 keV)

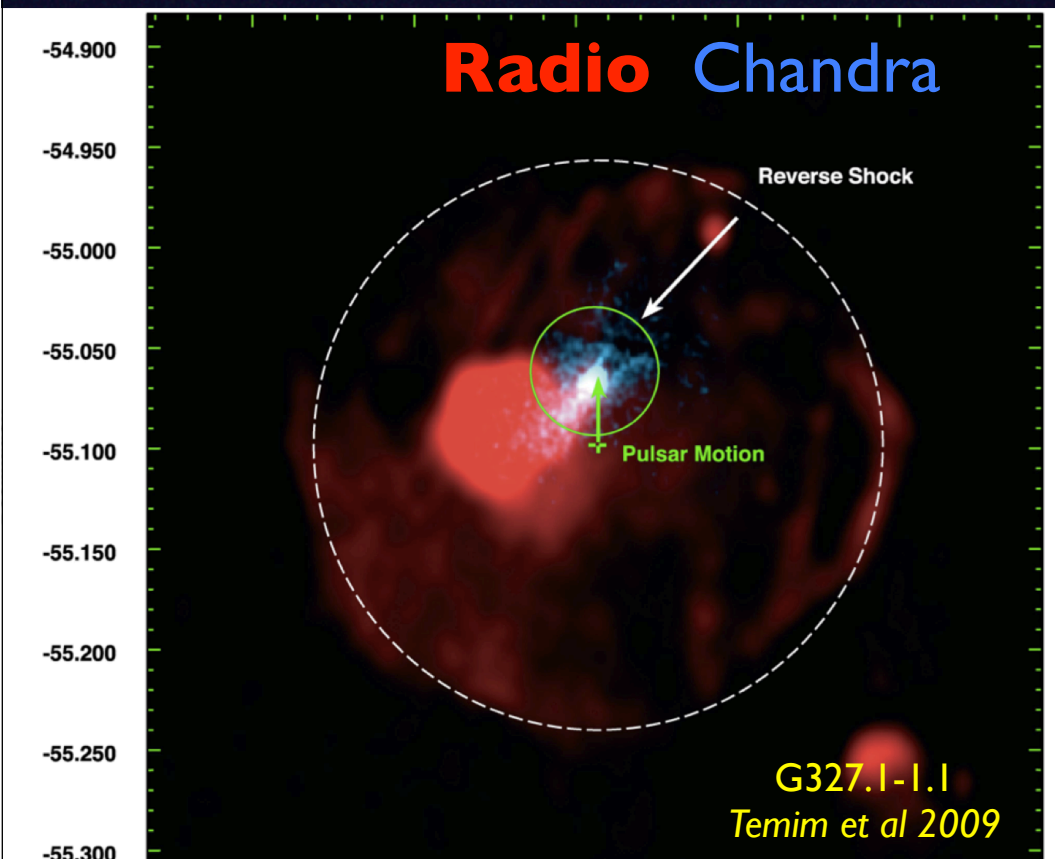
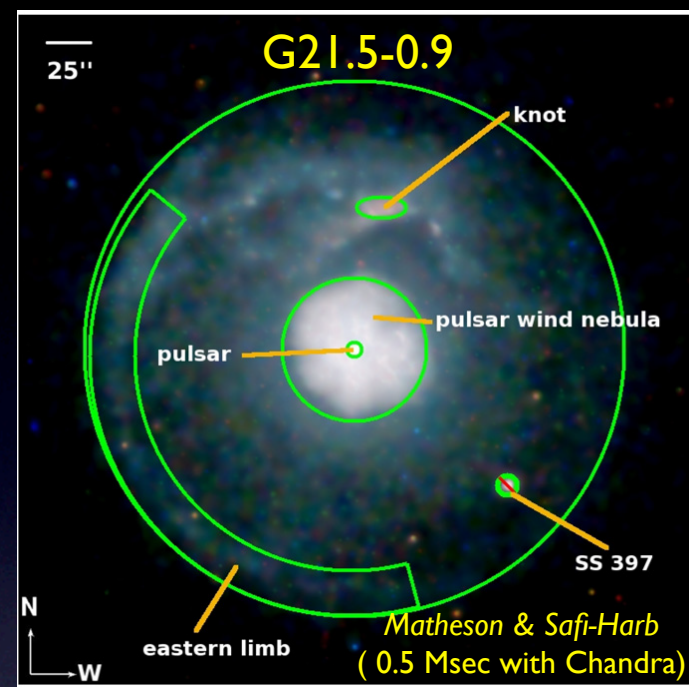
- ✓ searching for thermal emission from synchrotron dominated PWNe (and SNRs)
- ✓ simultaneous modelling of both the thermal & non-thermal plasma in SNR,



Astro-H and PWNe

“Naked” PWNe (Crab-like):

With the SXS, search for the long-sought **missed thermal emission** associated with the blast wave/ shocked ejecta (as hinted e.g. in G21.5-0.9).



Evolved/Crushed PWNe:

With the SXS (+HXD), one can study the **interaction between the reverse shock and the (crushed) PWN**. Mixed (soft) thermal and (hard) non-thermal X-ray emission detected, e.g. in G327.1-1.1.

Summary

- A long way since the discovery of 1st NS/SNR in 1968!
- Diversity (with still many questions):
 - **intrinsic** (NS properties, SN progenitor, ambient medium)
 - ✓ growing evidence for **shells** around Crab-like PWNe
 - ✓ growing evidence for **PWNe around highly magnetized neutron stars**
 - **Age effect/Evolution** (interaction with reverse shock, SNR shell, ambient medium)
 - PWNe as **pathfinders** for pulsars:
 - ✓ a low L_x does **not** necessarily imply a low $\dot{E}$.
 - ✓ look for pulsars in **peak of x-ray emission** (not necessarily radio)
- Near Future (high-energy):
 - ✓ NuSTAR (June 2012-; *hard x-ray emission*) Astro-H (2014; *thermal plasma in PWNe, broadband spectroscopy*). ASTROSAT and HXMT (*broadband/hard x-ray spectra*)
 - ✓ HESS II (Jul 26-), and other planned gamma-ray missions (CTA)

Thanks to...



SNR group at UofM

From left to right:

Harsha Kumar (PhD candidate, HBPs/Magnetars/SNRs)

Heather Matheson (PhD candidate, PWNe/PWNCat)

Gilles Ferrand (Postdoc, SNRcat, cosmic ray acceleration in SNRs)

Jennifer West (PhD candidate, radio/modelling B in SNRs)

SSH

Paul Edmon (former Postdoc, PWN simulations)

Erica Franzmann (former undergraduate)

Adam Rogers (postdoc, XFIT/spectroscopy)

Collaborators including Zaven Arzoumanian, Roland Kothes, Tom Landecker..

Contributions by the NS/PWN/SNR community

Thank you IAUS29I!