Pulsar Parallaxes, Bow Shock Nebulae and the Interstellar Medium

Shami Chatterjee & James M. Cordes

NRAO / Cornell University

Observables

- Astrometry: Proper Motions and Parallaxes

$\longrightarrow$ *Model-independent* D and $V_\perp$

Observables

- Astrometry: Proper Motions and Parallaxes
$\rightarrow$ *Model-independent* D and $V_\perp$
- Pulse Dispersion: $\int_0^D n_e\, ds$.
- Interstellar Scattering: $\Delta t_d,\ \Delta\nu_d$, Pulse Broadening.
- Multi-wavelength Observations:

  * Hα Imaging: shocked gas.

  * X-ray Spectra.

  * Radio and X-ray Imaging: PWN, SNRs, etc.

Observables

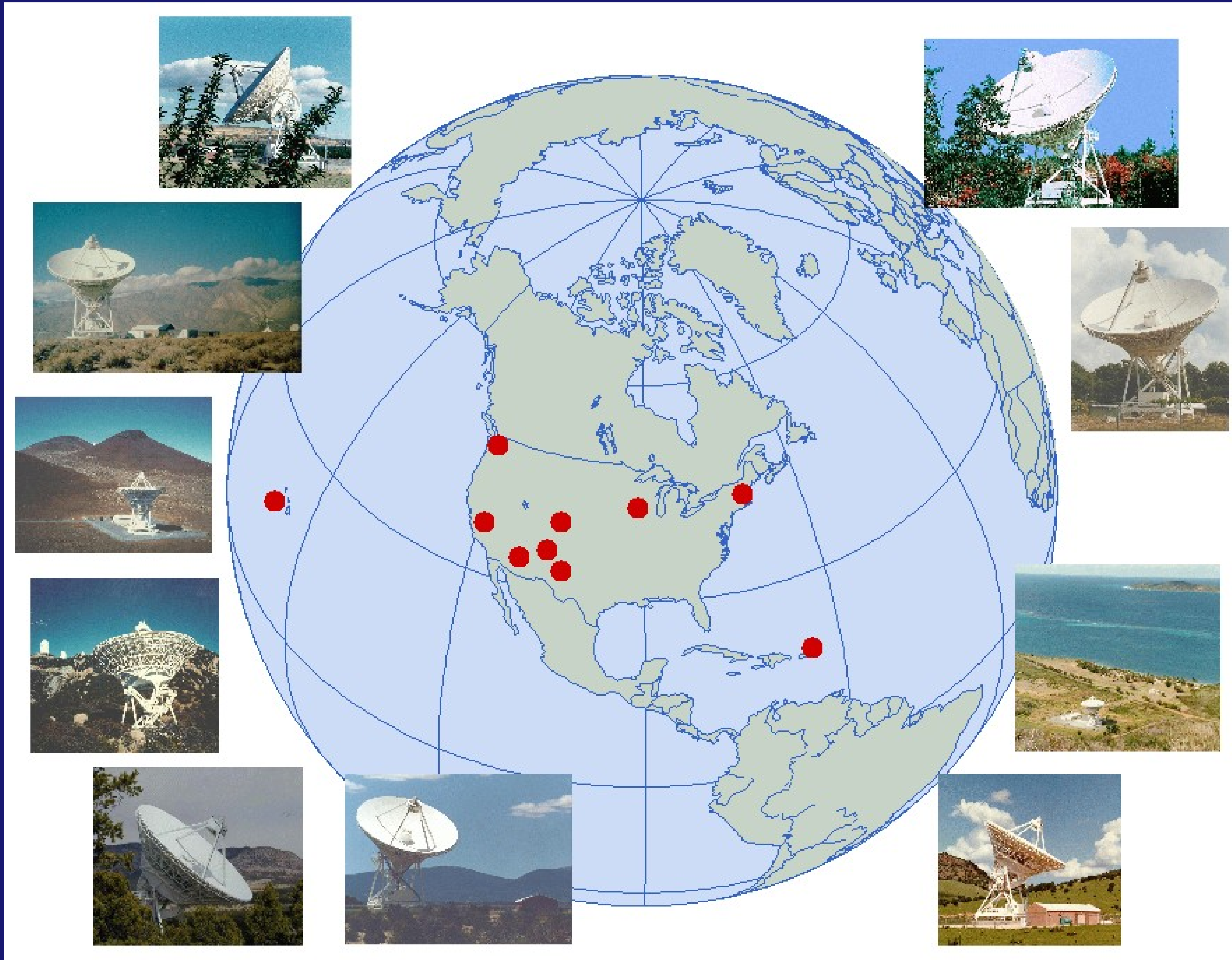
- Astrometry: Proper Motions and Parallaxes
$\rightarrow$ *Model-independent* D and $V_\perp$
- Pulse Dispersion: $\int_0^D n_e\, ds$.
- Interstellar Scattering: $\Delta t_d,\ \Delta\nu_d$, Pulse Broadening.
- Multi-wavelength Observations:

  * Hα Imaging: shocked gas.

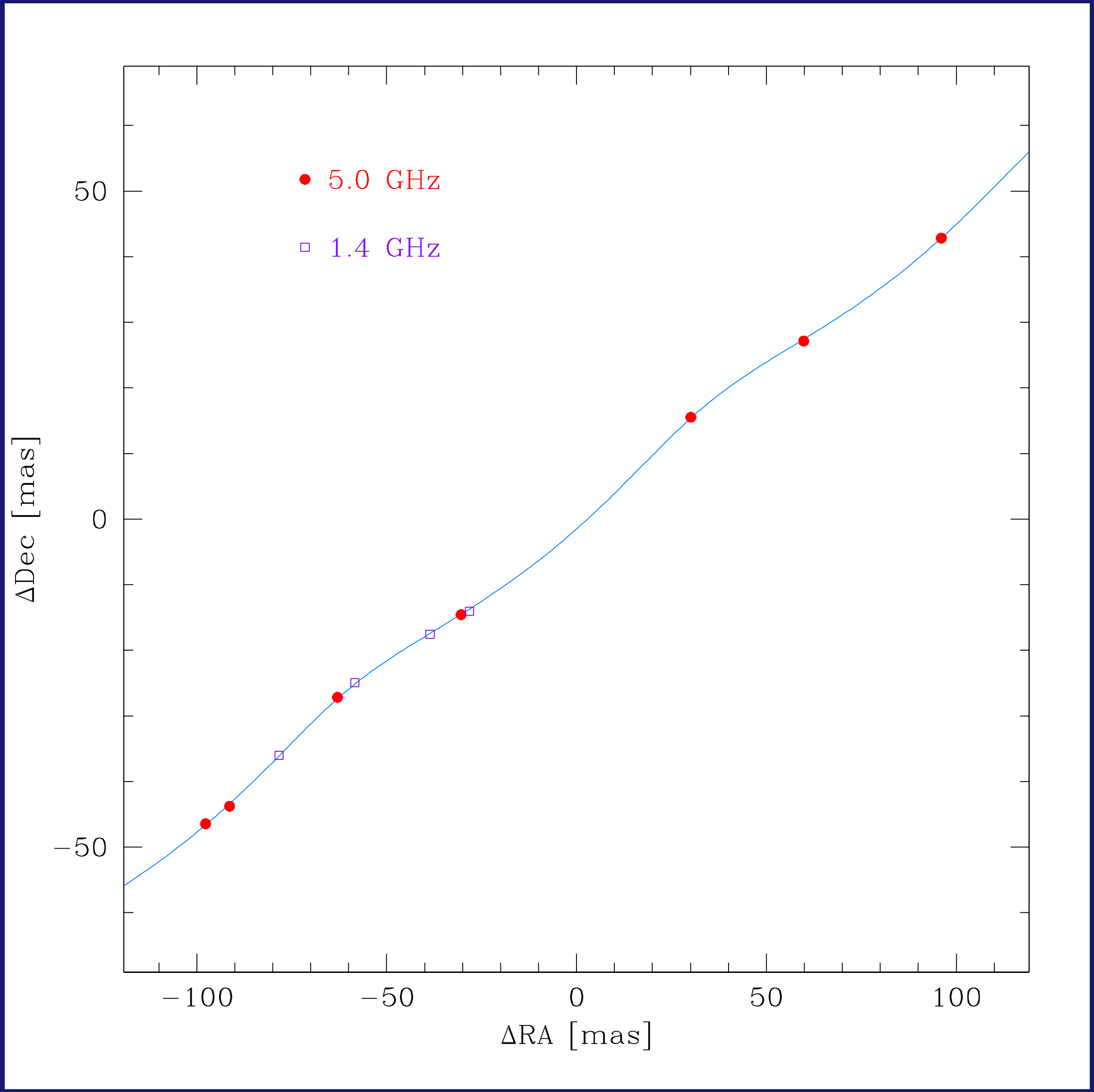
  * X-ray Spectra.

  * Radio and X-ray Imaging: PWN, SNRs, etc.

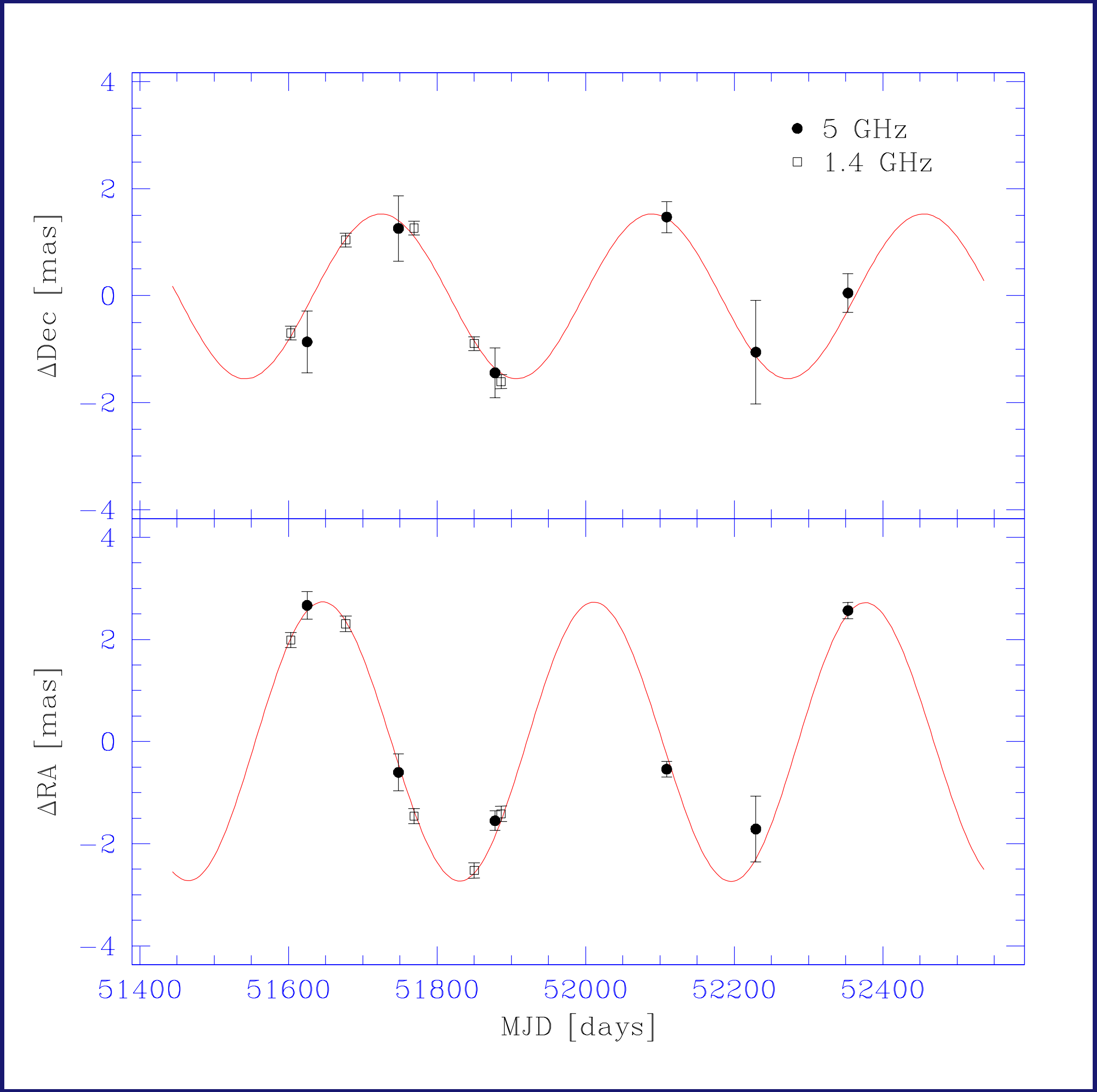
Multiple scientific applications – but first, how do we do it?



B1929+10: 5 GHz and 1.4 GHz Observations



B1929+10: 5 GHz and 1.4 GHz Observations



B1929+10: 5 GHz and 1.4 GHz Observations

$\mu_\alpha = 94.09 \pm 0.11$ mas yr^{-1}

$\mu_\delta = 42.99 \pm 0.16$ mas yr^{-1}

Parallax $\pi = 2.77 \pm 0.07$ mas

$\Rightarrow$ Distance $= 361^{+10}_{-8}$ pc

$\Rightarrow$ Velocity $= 177^{+4}_{-5}$ km s^{-1}.

We can achieve sub-milliarcsecond astrometry: an order of magnitude better than previous capabilities.

Scientific Questions

- Origins: SNR associations and NS birth sites in stellar clusters; true ages.

Scientific Questions

- Origins: SNR associations and NS birth sites in stellar clusters; true ages.
- Astrophysics: NS atmospheres, cooling curves and nuclear Equations of State from spectra and absolute distances.

Scientific Questions

- Origins: SNR associations and NS birth sites in stellar clusters; true ages.
- Astrophysics: NS atmospheres, cooling curves and nuclear Equations of State from spectra and absolute distances.
- Astrophysics: Constraints on supernova core collapse.
- Evolution: NS distribution and population velocities.

Scientific Questions

- Origins: SNR associations and NS birth sites in stellar clusters; true ages.
- Astrophysics: NS atmospheres, cooling curves and nuclear Equations of State from spectra and absolute distances.
- Astrophysics: Constraints on supernova core collapse.
- Evolution: NS distribution and population velocities.
- Environment: Galactic n_e models, model the local ISM.

$\longrightarrow$ e.g., using pulsar scintillation.
$\longrightarrow$ e.g., using NS bow shock nebulae.

Scientific Questions

- Origins: SNR associations and NS birth sites in stellar clusters; true ages.
- Astrophysics: NS atmospheres, cooling curves and nuclear Equations of State from spectra and absolute distances.
- Astrophysics: Constraints on supernova core collapse.
- Evolution: NS distribution and population velocities.
- Environment: Galactic n_e models, model the local ISM.
  $\longrightarrow$ e.g., using pulsar scintillation.
  $\longrightarrow$ e.g., using NS bow shock nebulae.
- Verify solar system–extragalactic reference frame ties.

Scientific Questions

• Origins: SNR associations and NS birth sites in stellar clusters; true ages.

• Astrophysics: NS atmospheres, cooling curves and nuclear Equations of State from spectra and absolute distances.

• Astrophysics: Constraints on supernova core collapse.

• Evolution: NS distribution and population velocities.

• Environment: Galactic n_e models, model the local ISM.
$\longrightarrow$ e.g., using pulsar scintillation.
$\longrightarrow$ e.g., using NS bow shock nebulae.

• Verify solar system–extragalactic reference frame ties.

$\Rightarrow$ In each case, precise astrometry enables new science.

Neutron Star Bow Shocks

Supersonic motion of neutron stars through the ISM
$\Rightarrow$ Shocked layer: ram pressure balance is established between the relativistic NS wind and the medium.

Neutron Star Bow Shocks

Supersonic motion of neutron stars through the ISM
$\Rightarrow$ Shocked layer: ram pressure balance is established between the relativistic NS wind and the medium.

$$\rho_a v_*^2 = \frac{\dot{m}_w v_w}{4\pi R_0^2} \quad \Rightarrow \quad R_0 = \sqrt{\frac{\dot{E}}{4\pi c \rho_a v_*^2}}.$$

Neutron Star Bow Shocks

Supersonic motion of neutron stars through the ISM
$\Rightarrow$ Shocked layer: ram pressure balance is established between the relativistic NS wind and the medium.

$$\rho_a v_*^2 = \frac{\dot{m}_w v_w}{4\pi R_0^2} \quad \Rightarrow \quad R_0 = \sqrt{\frac{\dot{E}}{4\pi c \rho_a v_*^2}}.$$

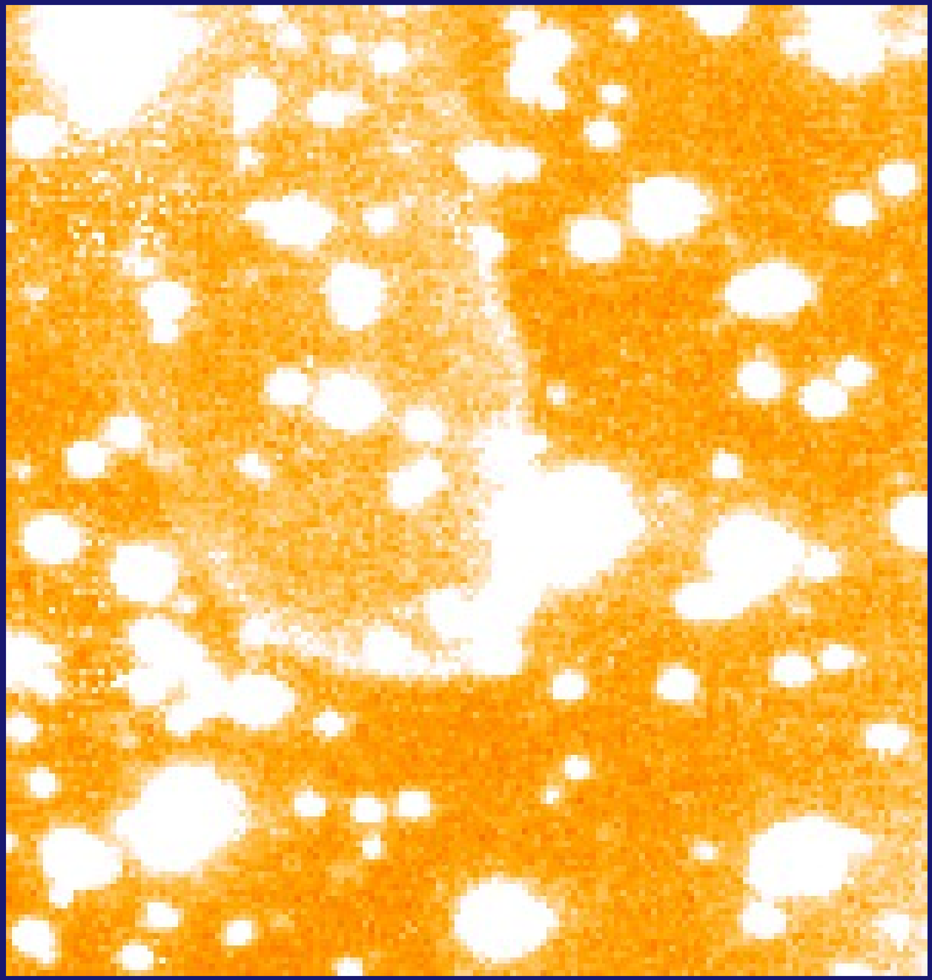
- Outer shock: collisional excitation, possible Hα emission.
- Inner shock: relativistic NS wind, possible synchrotron radiation.

An Example: B1957+20

- Millisecond (recycled) pulsar: period = 1.6 ms.
- Old, low field: $B = 1.4 \times 10^8$ G; $\tau = 1.5 \times 10^9$ yr.
- Binary system: “Black Widow” pulsar.
- $l = 59.2°;\ b = -4.7°;\ D = 1.5$ kpc.

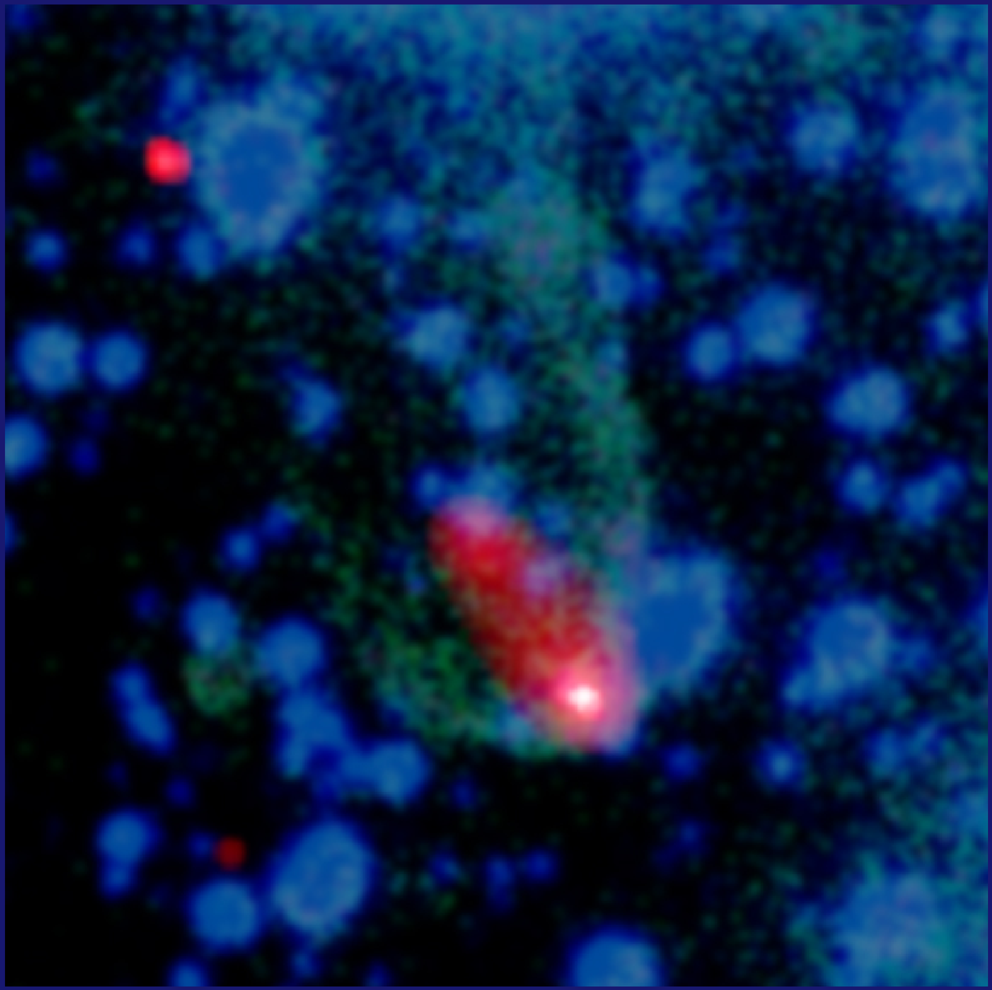
- Spindown Energy $\dot{E} = 1.6 \times 10^{35}$ erg/s.
- Proper motion $\mu = 30.4$ mas/yr $\Rightarrow$ V = 220 km/s.

An Example: B1957+20



Hα bow shock nebula: Kulkarni & Hester (1988)

An Example: B1957+20



X-ray tail from relativistic wind: Stappers et al. (2003)

A Very Different Example: B2224+65

- Ordinary young pulsar: period = 0.68 ms.
- $B = 2.6 \times 10^{12}$ G; $\tau = 1.1 \times 10^{6}$ yr.
- $l = 108.6°; \; b = 6.9°; \; D = 1.9$ kpc.

- Spindown Energy $\dot{E} = 1.2 \times 10^{33}$ erg/s.

$\Rightarrow$ A garden-variety pulsar....

A Very Different Example: B2224+65

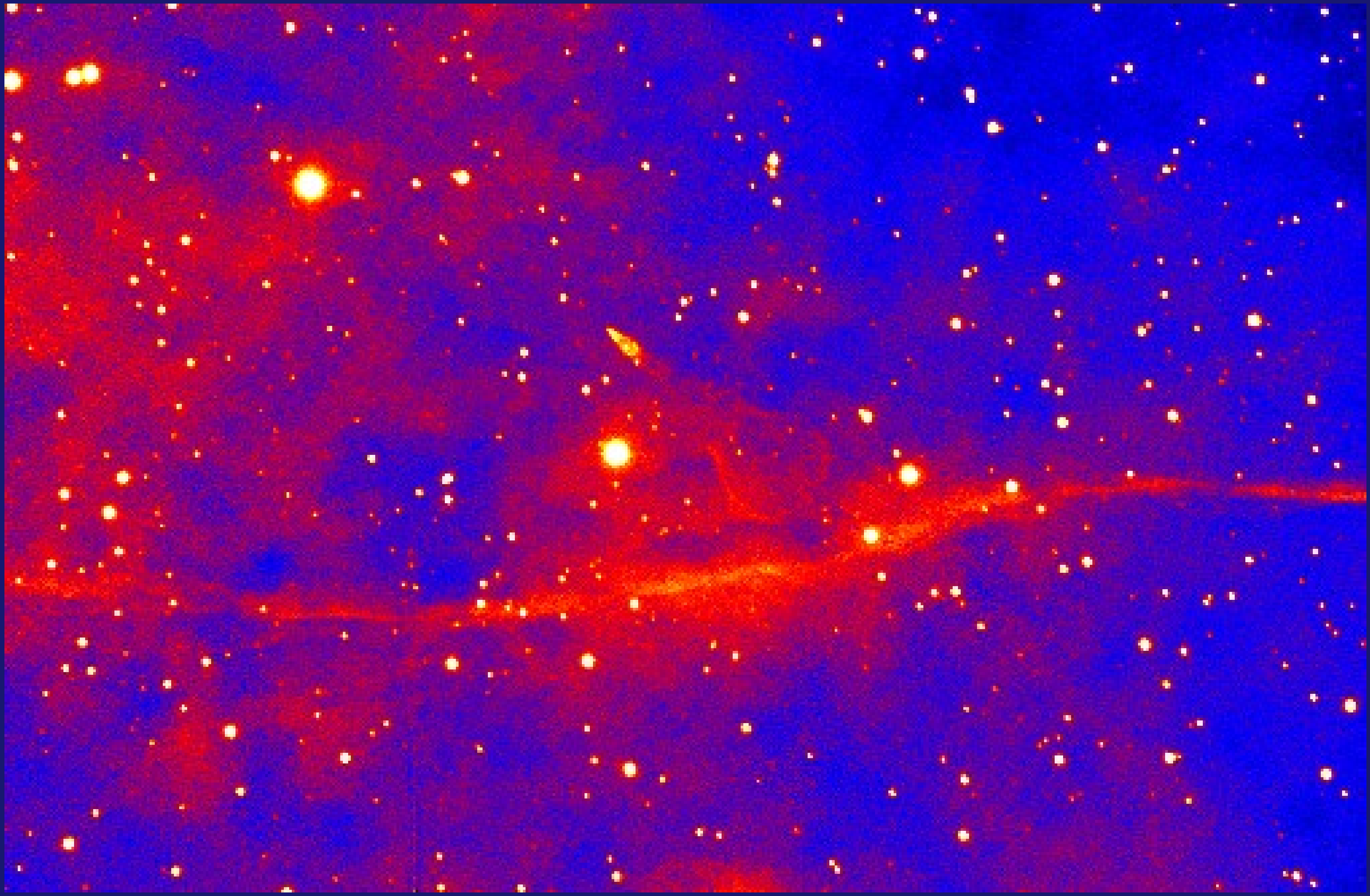
- Ordinary young pulsar: period = 0.68 ms.
- $B = 2.6 \times 10^{12}$ G; $\tau = 1.1 \times 10^{6}$ yr.
- $l = 108.6°;\ b = 6.9°;\ D = 1.9$ kpc.

- Spindown Energy $\dot{E} = 1.2 \times 10^{33}$ erg/s.

$\Rightarrow$ A garden-variety pulsar....

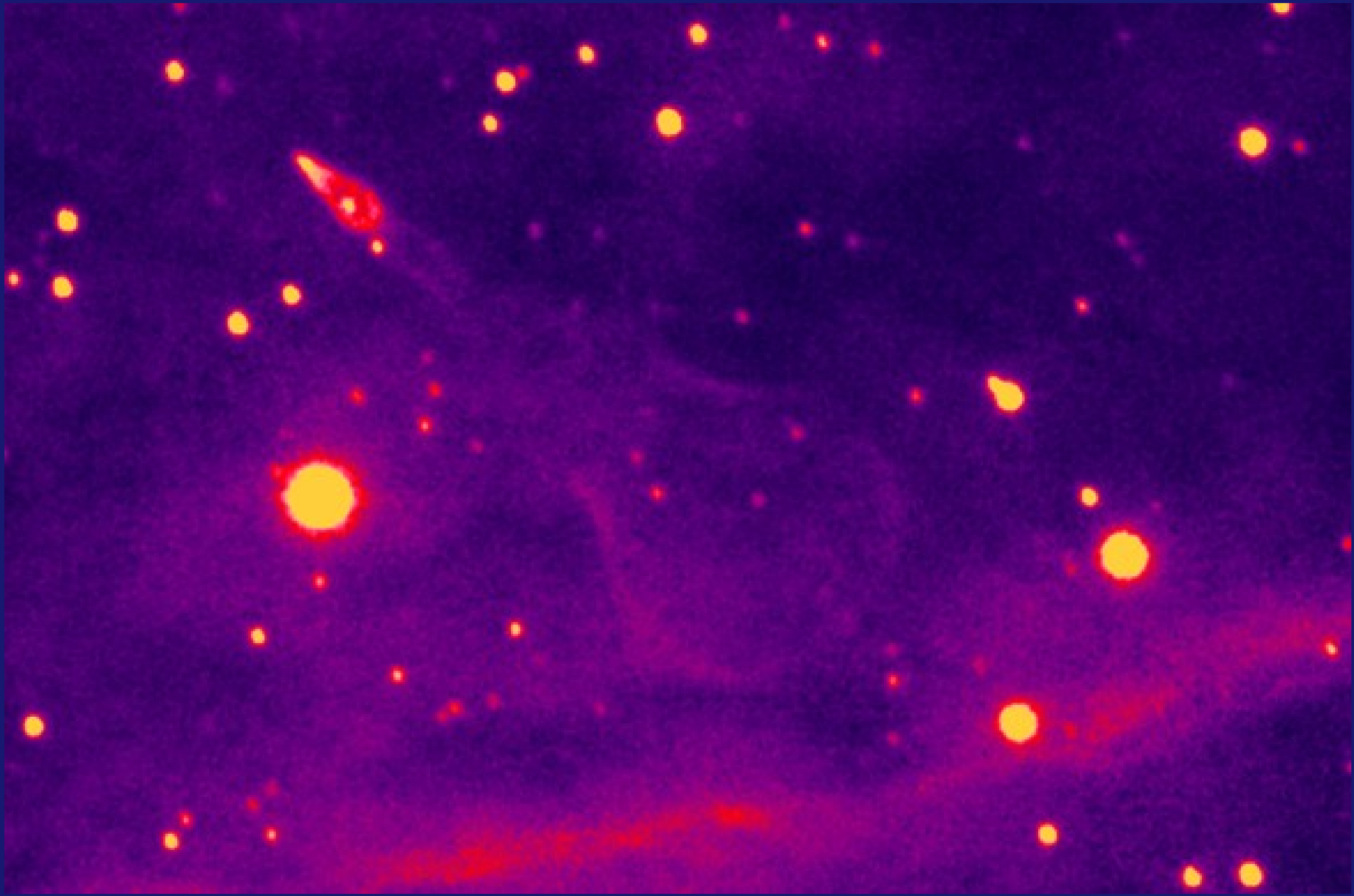
- *But:* proper motion $\mu = 182$ mas/yr $\Rightarrow$ V = 1640 km/s!

B2224+65: The Guitar Nebula



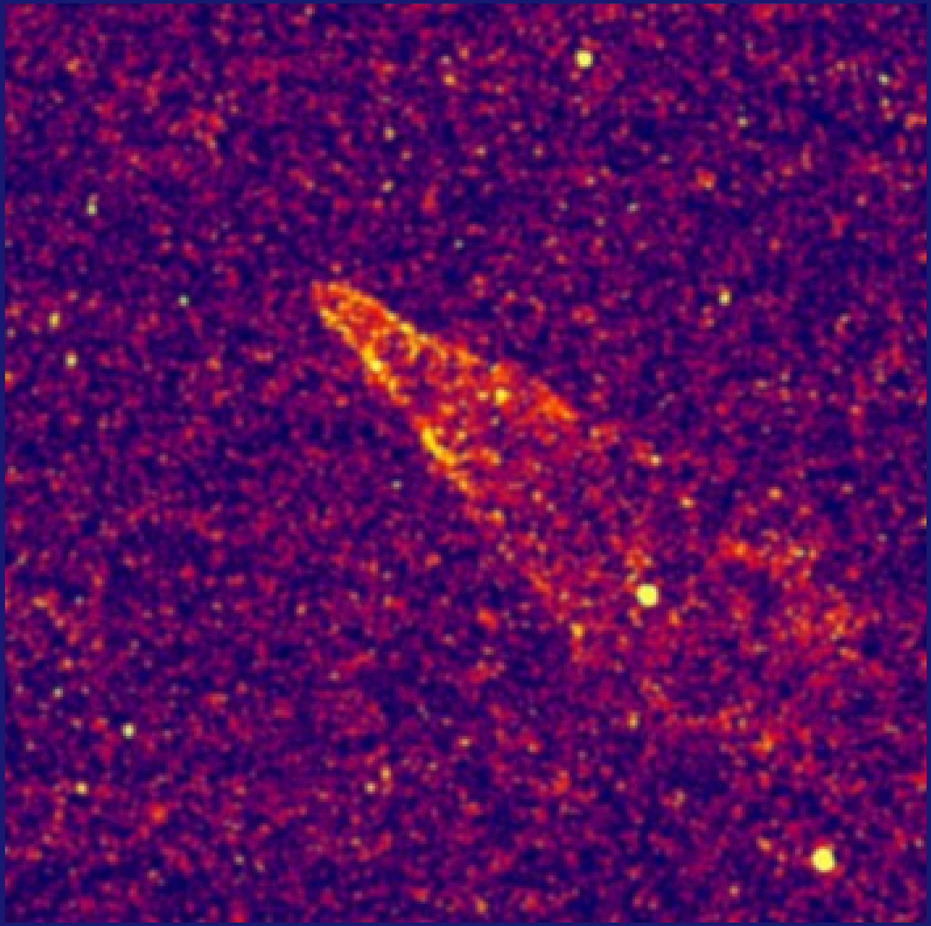
$H\alpha$ bow shock nebula: Cordes, Romani & Lundgren (1993)

B2224+65: The Guitar Nebula



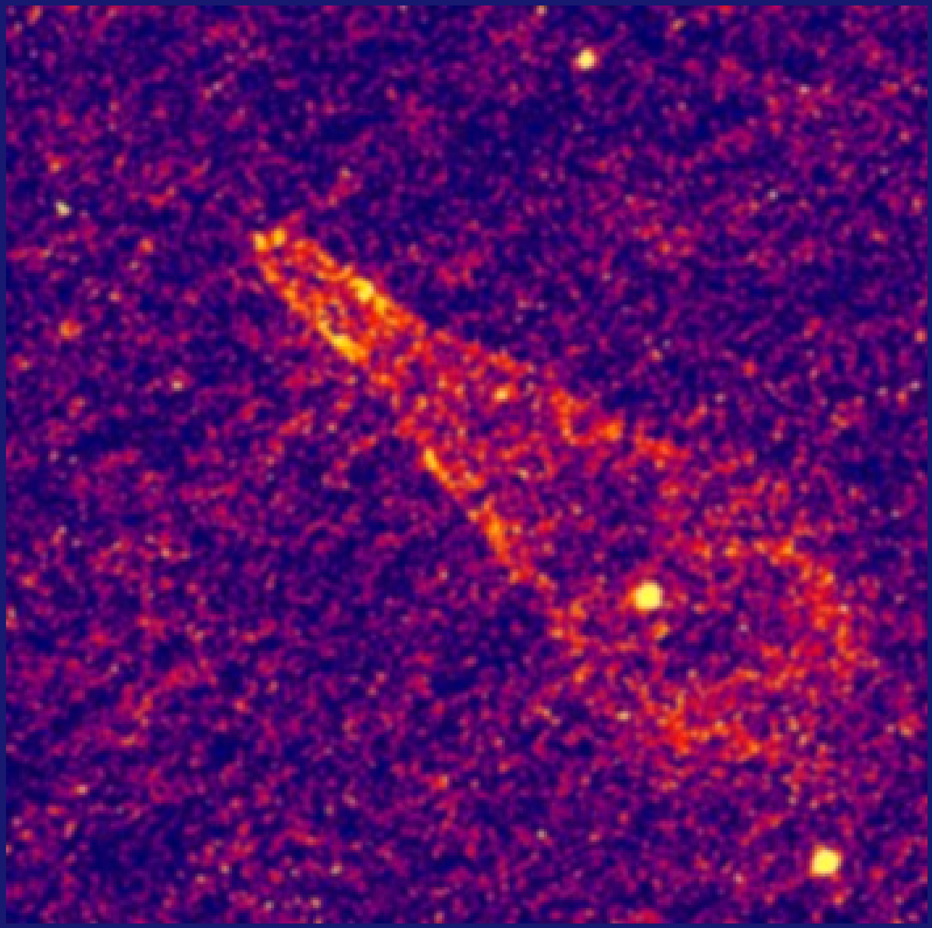
Palomar image of the Guitar Nebula

The Guitar Nebula: Time Evolution



- 1994 December: Narrow-band Hα; $T_{\rm int}$ = 7200 s; Drizzled.

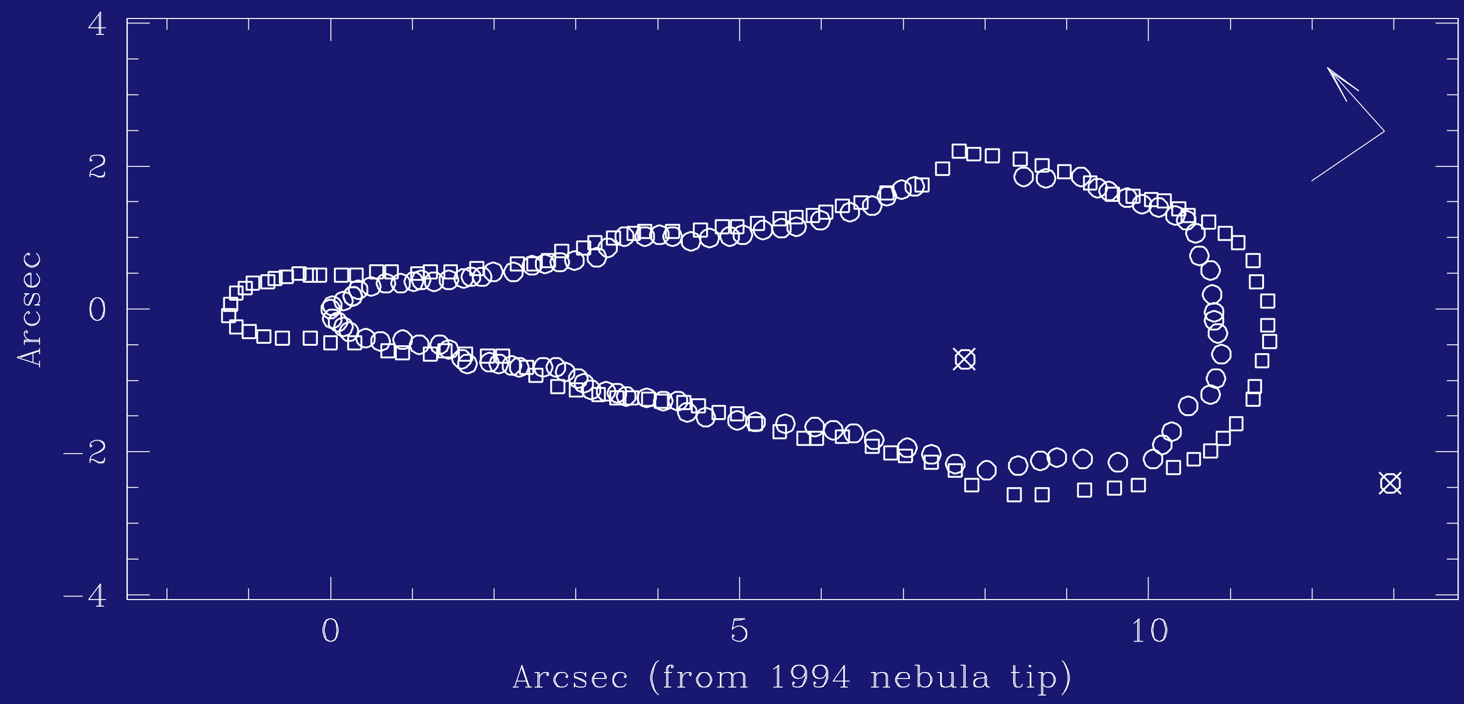
The Guitar Nebula: Time Evolution



- 2001 December: Narrow-band Hα; $T_{\rm int}$ = 17600 s; Drizzled.

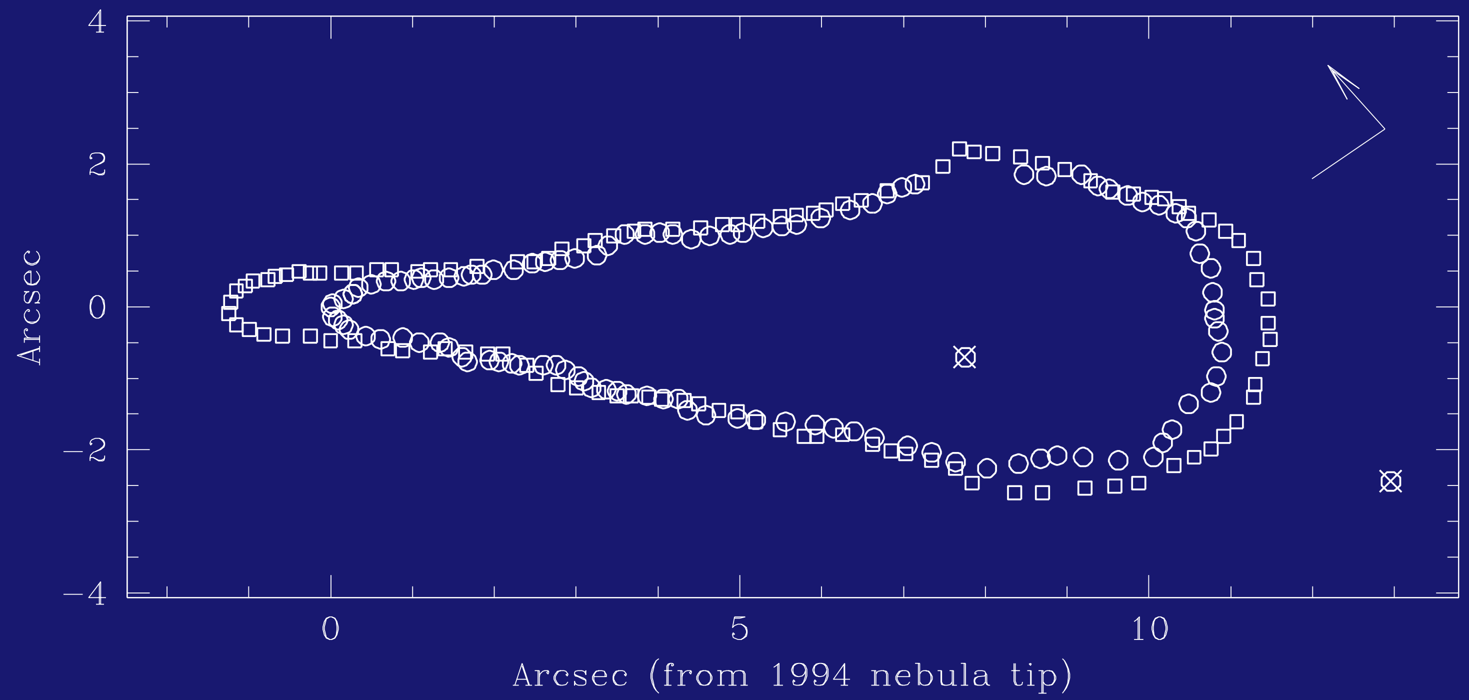
The Guitar Nebula: Time Evolution

- The NS appears to be emerging from a region of enhanced density: stand off radius increases, and ρ reduced by 33%.



The Guitar Nebula: Time Evolution

- The NS appears to be emerging from a region of enhanced density: stand off radius increases, and ρ reduced by 33%.
- The confined portions of the nebula are brightened; the nebula widens as the NS moves away (as expected).



The Guitar Nebula: Time Evolution

- The NS appears to be emerging from a region of enhanced density: stand off radius increases, and ρ reduced by 33%.
- The confined portions of the nebula are brightened; the nebula widens as the NS moves away (as expected).
- The rear end of the shock expands: confined wind creates the bright head?

The Guitar Nebula: Time Evolution

- The NS appears to be emerging from a region of enhanced density: stand off radius increases, and ρ reduced by 33%.
- The confined portions of the nebula are brightened; the nebula widens as the NS moves away (as expected).
- The rear end of the shock expands: confined wind creates the bright head?

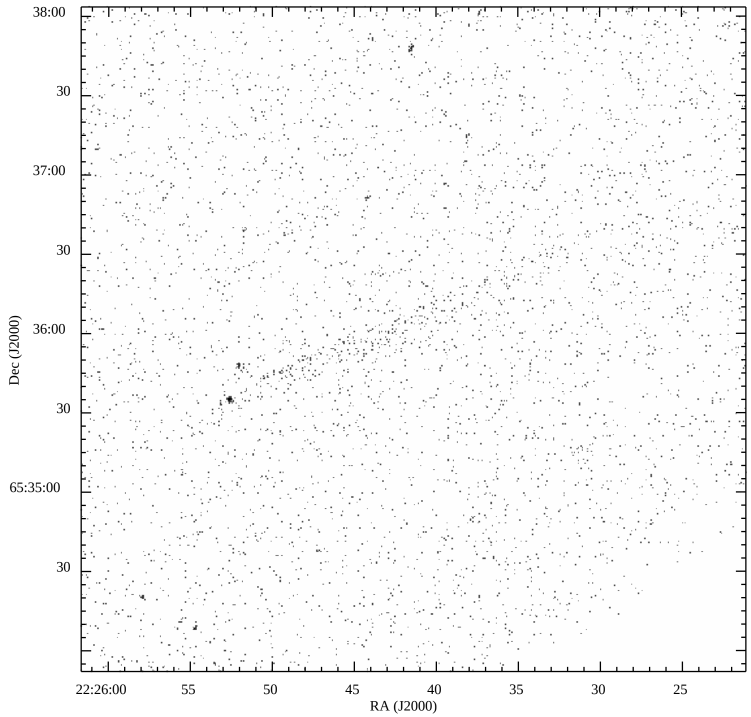
- Enables a detailed understanding of the ISM in the area.
- Probe (an)isotropy of the NS relativistic wind
+ the role of instabilities in the time evolution.

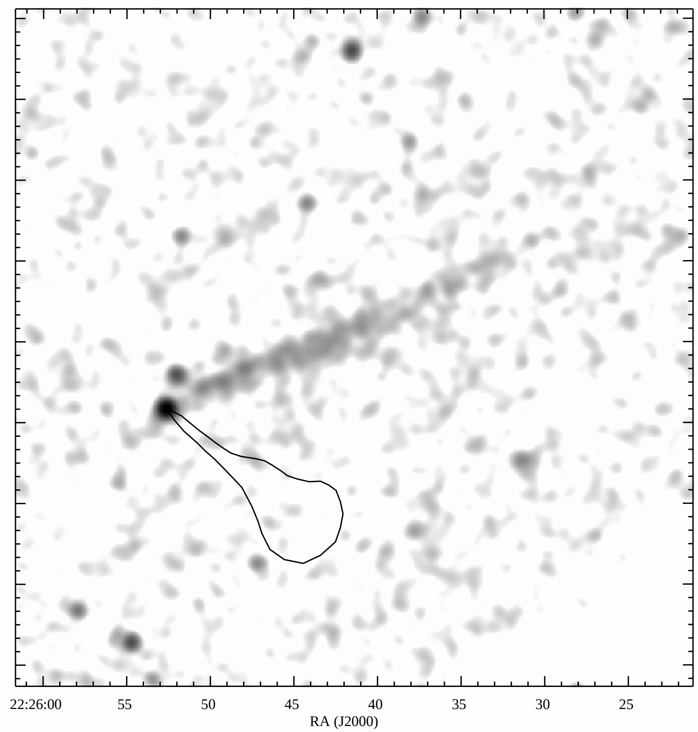
The Guitar Nebula in X-rays

Chandra observations show a hot spot and an X-ray feature...

The Guitar Nebula in X-rays

Chandra observations show a hot spot and an X-ray feature...

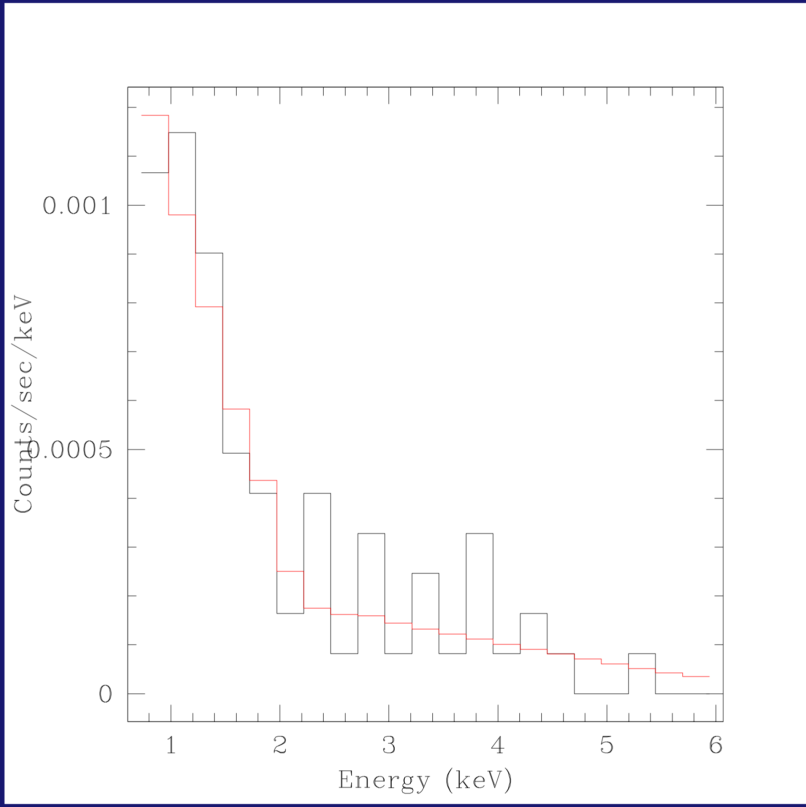




... but not in the expected direction.

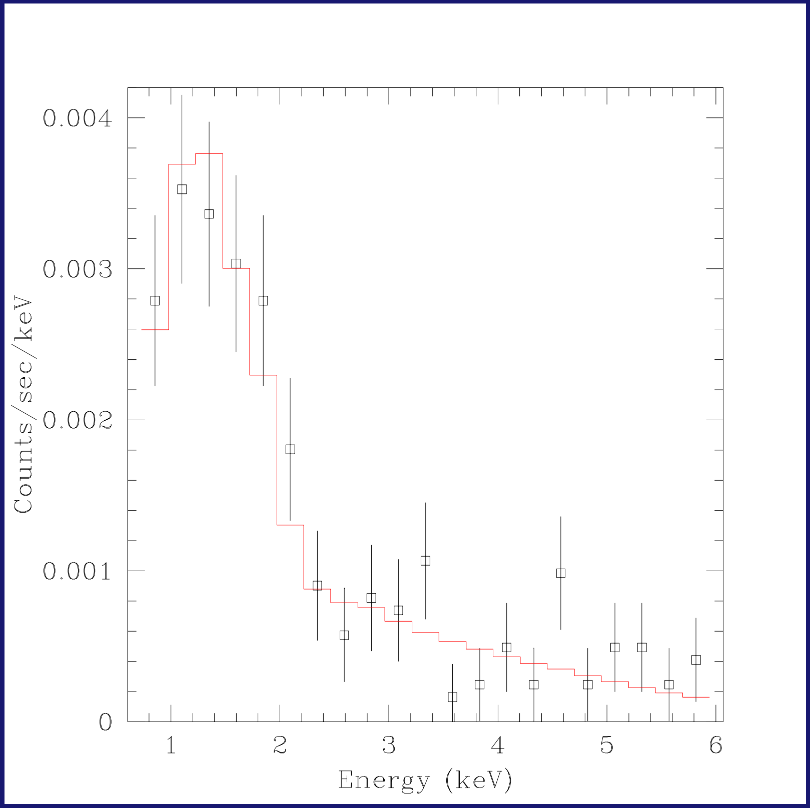
The Guitar Nebula in X-rays

- Hot spot: power law, consistent with shocked ISM and magnetospheric emission.



The Guitar Nebula in X-rays

- Hot spot: power law, consistent with shocked ISM and magnetospheric emission.
- Elongated feature: harder spectrum than hot spot, can be modeled by absorbed thermal bremsstrahlung.



The Guitar Nebula in X-rays

• Hot spot: power law, consistent with shocked ISM and magnetospheric emission.

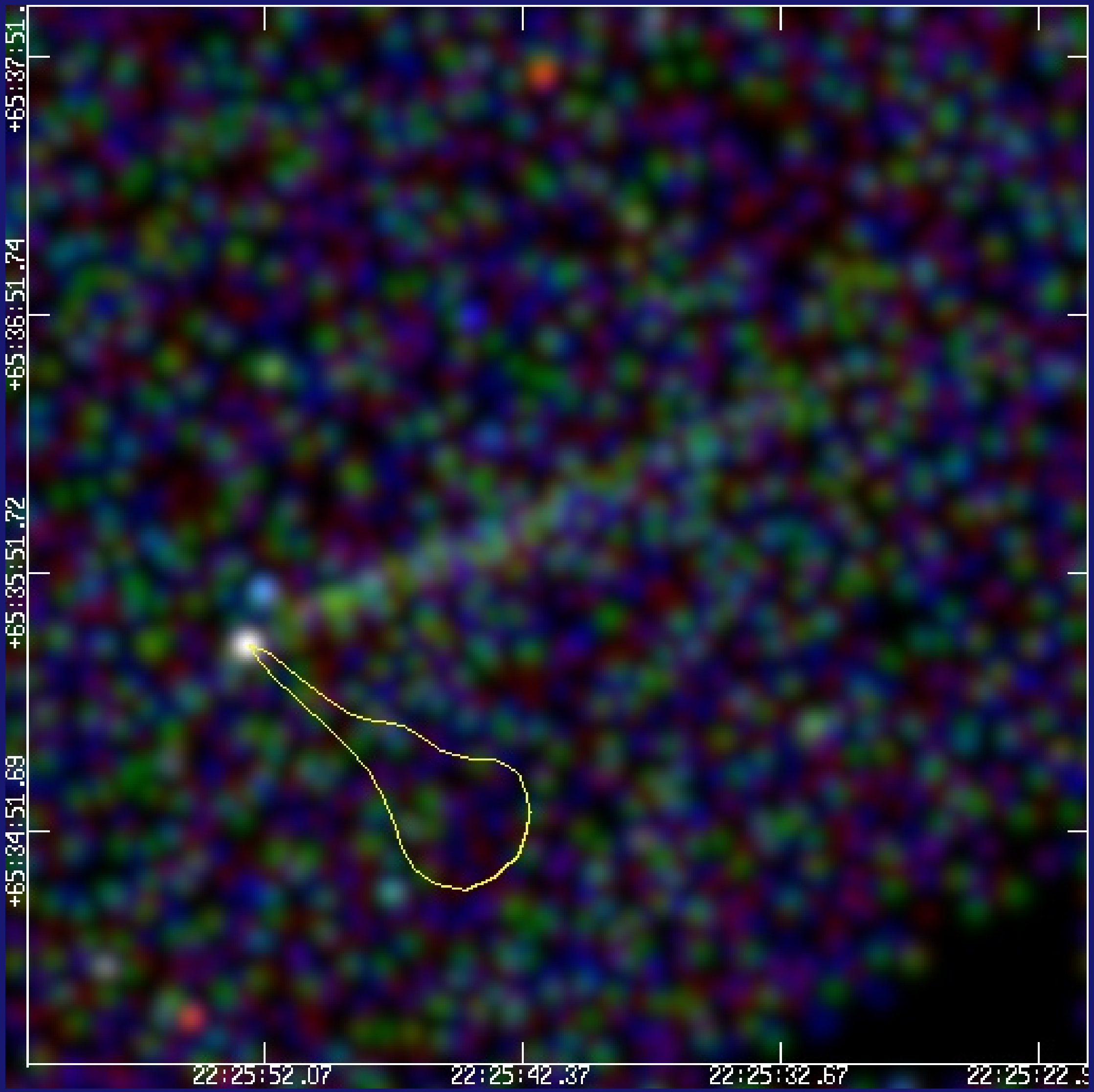
• Elongated feature: harder spectrum than hot spot, can be modeled by absorbed thermal bremsstrahlung.

$\longrightarrow$ Magnetic reconnection with the ISM field?

$\longrightarrow$ Polar jet, as seen in Crab, Vela, other young NS?

$\longrightarrow$ Leakage of relativistic wind particles along pre-existing filament?

The Guitar Nebula in X-rays



Other Observed NS Bow Shocks

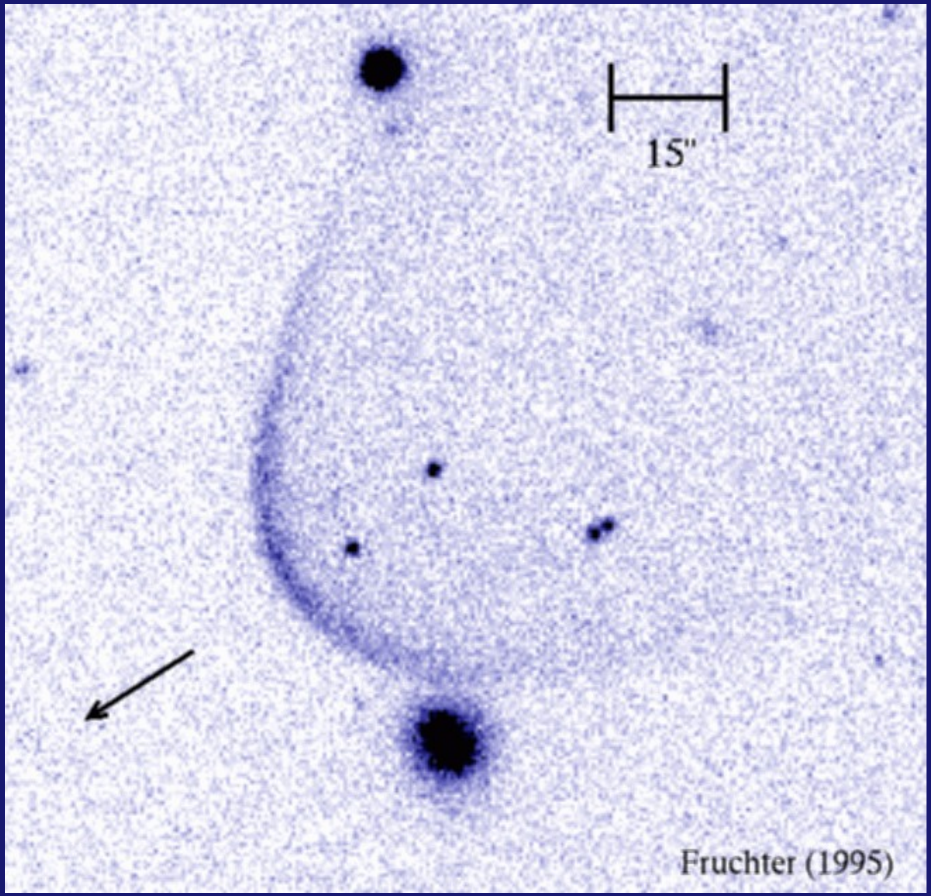
- Five known Hα pulsar bow shocks;
  one bow shock produced by a radio-quiet NS.
- A handful of radio and X-ray pulsar wind nebulae.

- Some other examples follow:

$\Rightarrow$ Note the diversity of objects: MSPs, radio quiet NS, ordinary garden-variety pulsars.

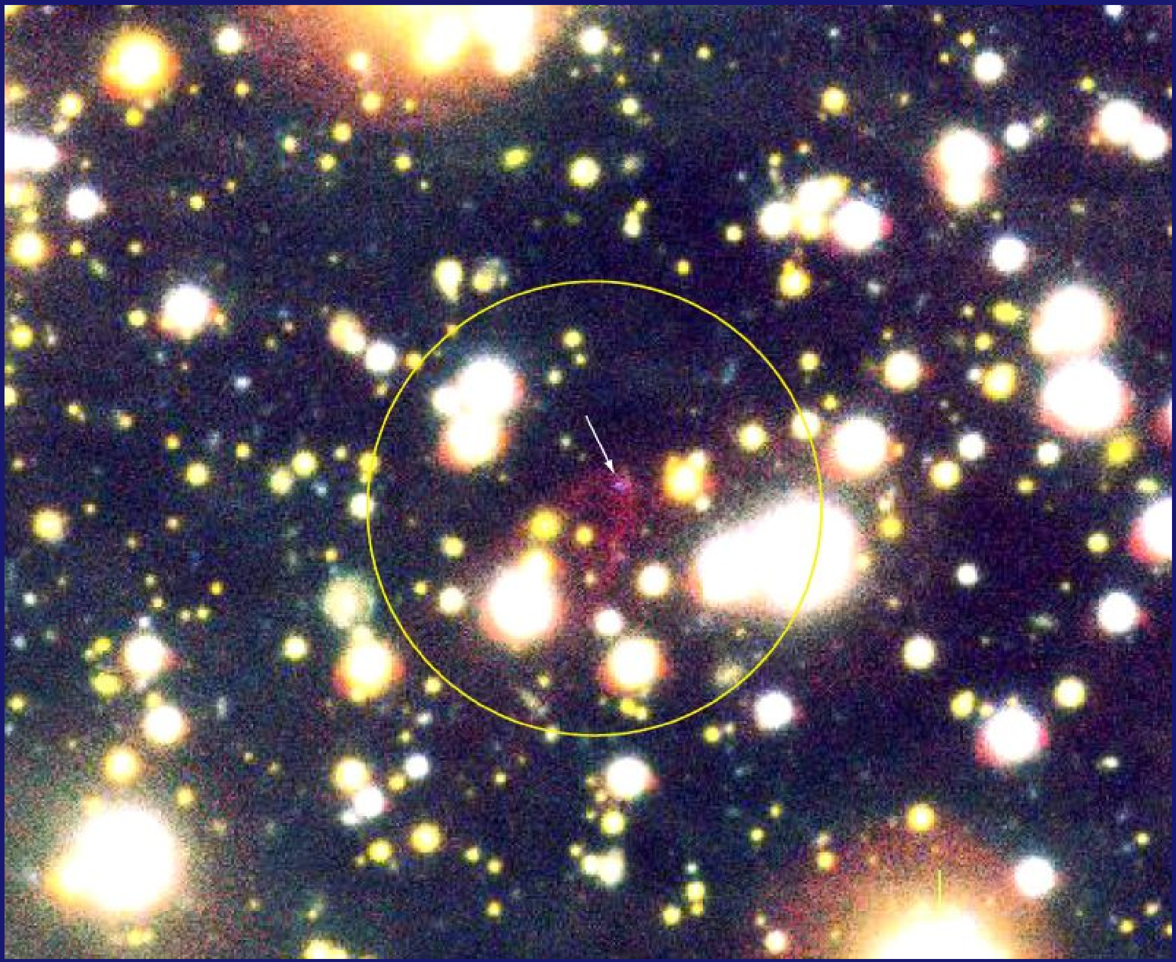
$\Rightarrow$ Also note the diversity of nebular shapes.

Other Observed NS Bow Shocks



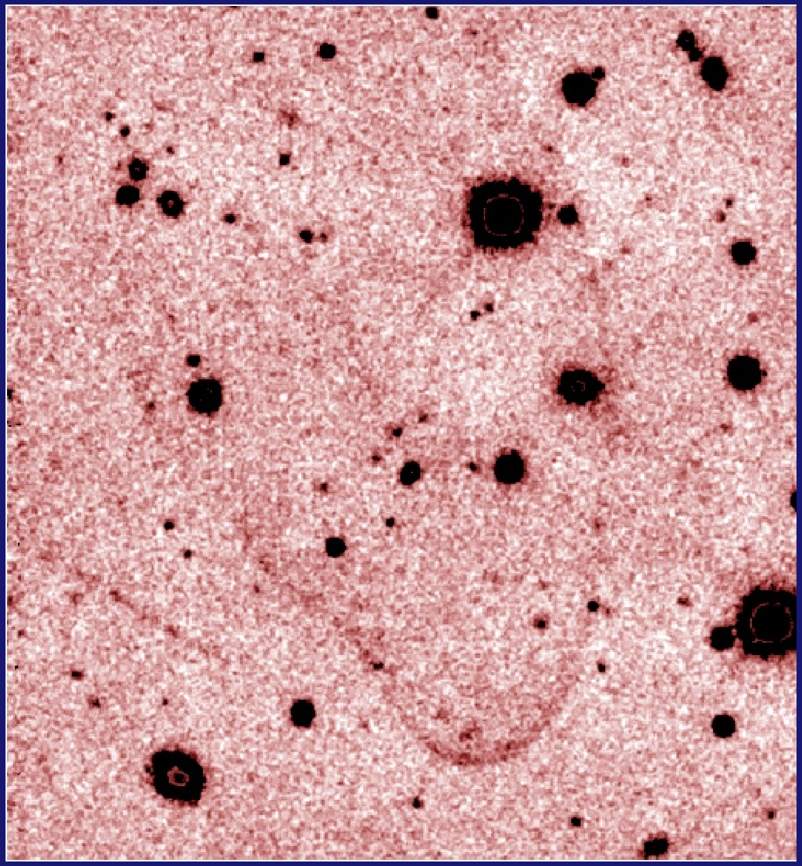
J0437–4715: millisecond pulsar
(Bell et al. 1995)

Other Observed NS Bow Shocks



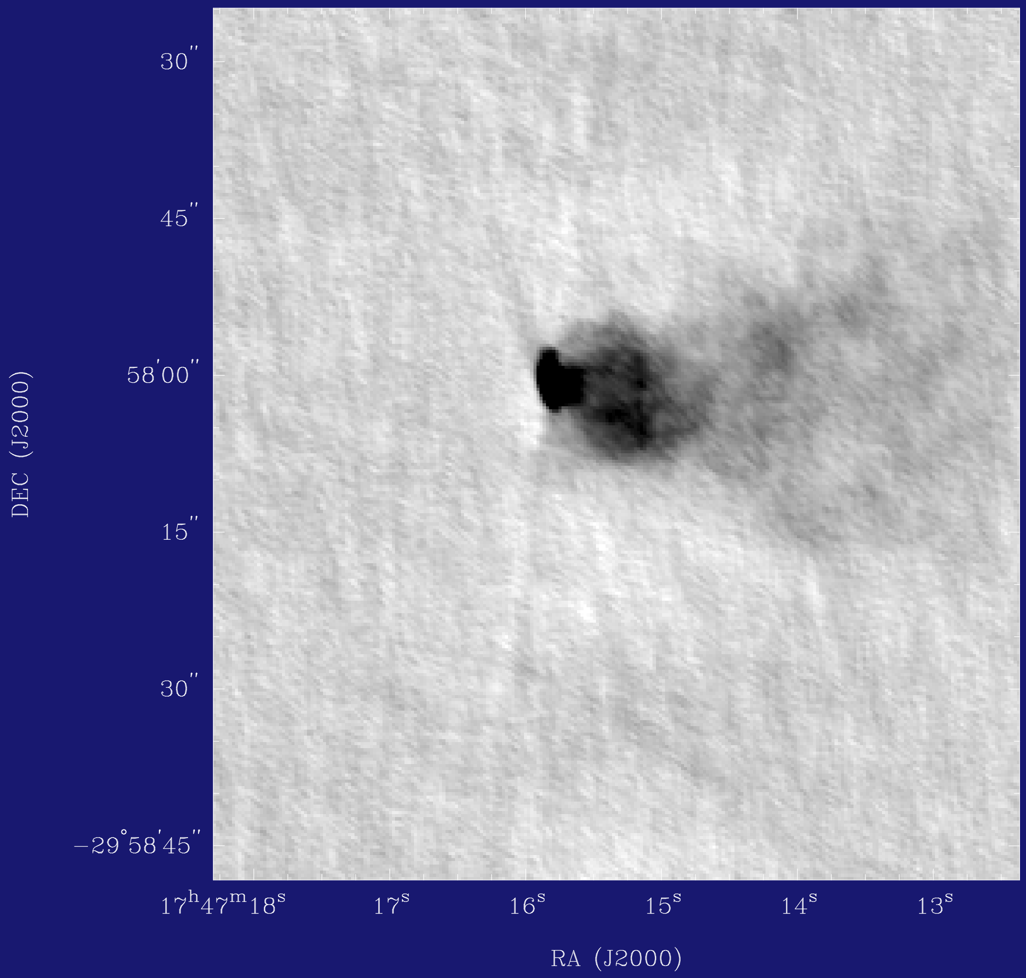
RX J1856.5−3754: radio quiet NS
(van Kerkwijk & Kulkarni 2001)

Other Observed NS Bow Shocks



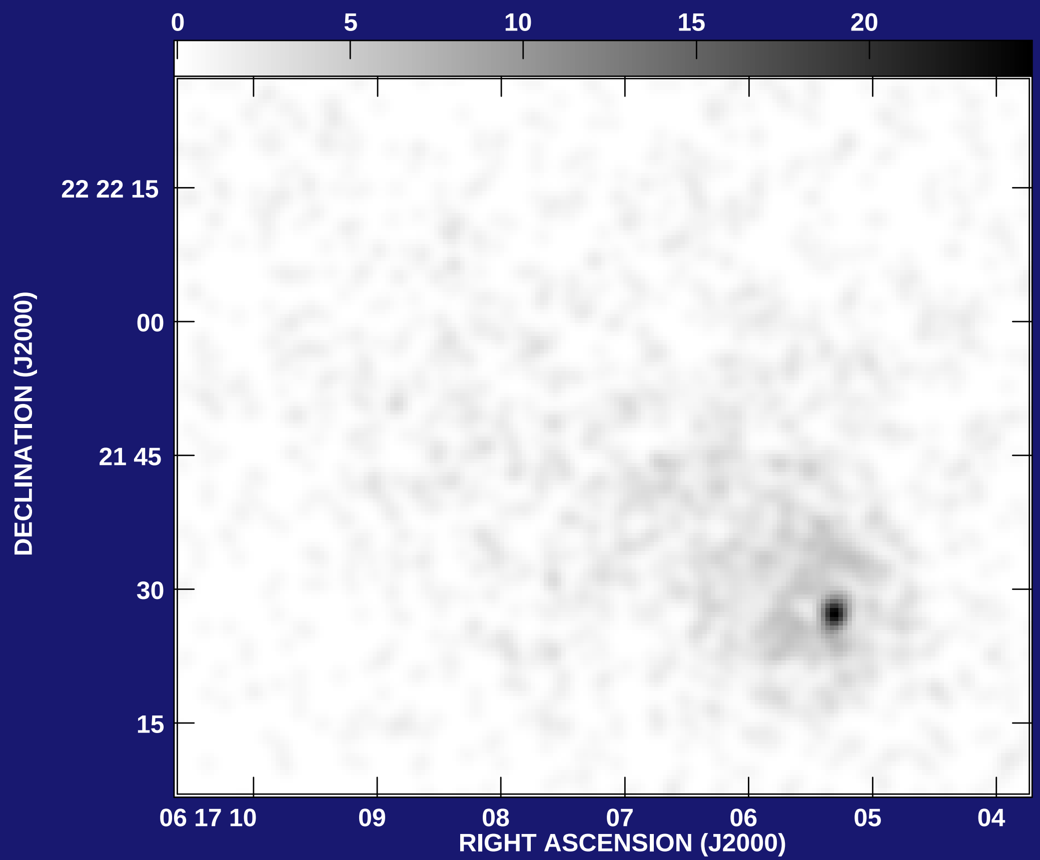
J2124−3358: millisecond pulsar
(Gaensler, Jones & Stappers 2002)

Other Observed NS Bow Shocks



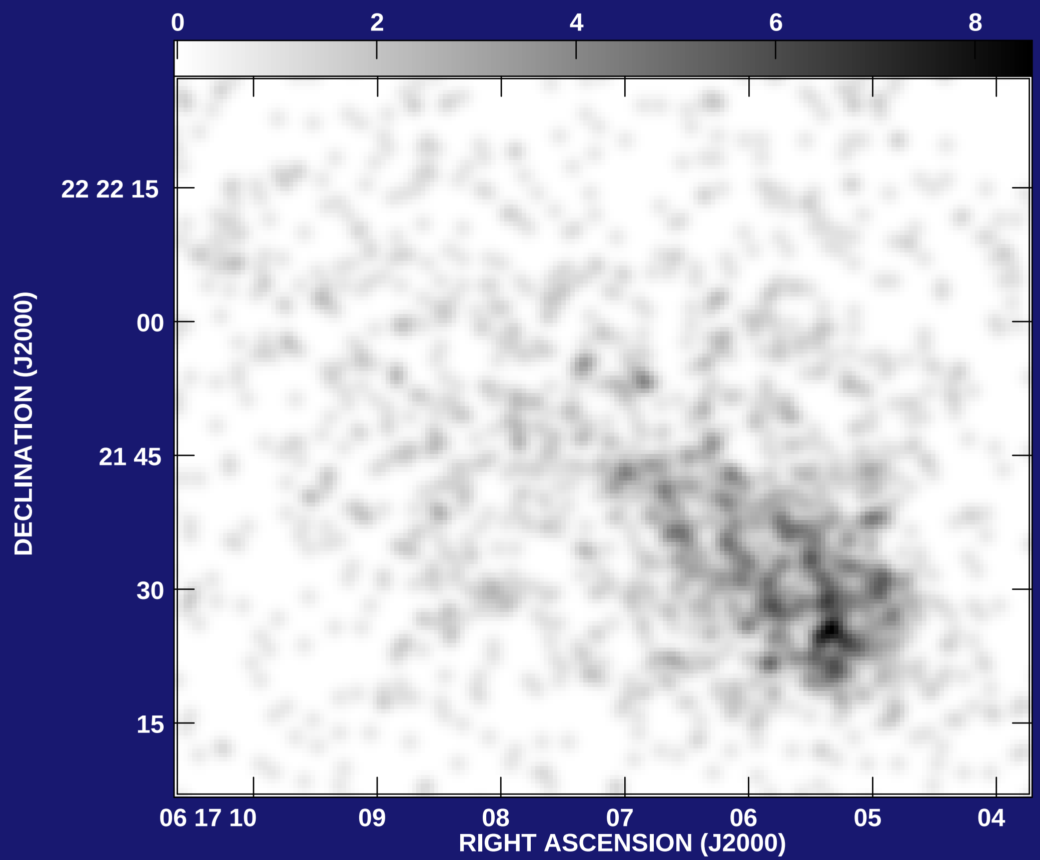
The Mouse: Yusef-Zadeh & Bally 1987
J1747−2958: Camilo et al. 2002

Other Observed NS Bow Shocks



CXOU J0617.0+2221: soft (< 2.1 keV) X-rays
Radio-undetected NS in IC443 (Olbert et al. 2001)

Other Observed NS Bow Shocks



CXOU J0617.0+2221: hard (> 2.1 keV) X-rays
Radio-undetected NS in IC443 (Olbert et al. 2001)

Scaling for Bow Shock Nebulae

Measure the stand-off angle for Hα bow shocks: test scaling.

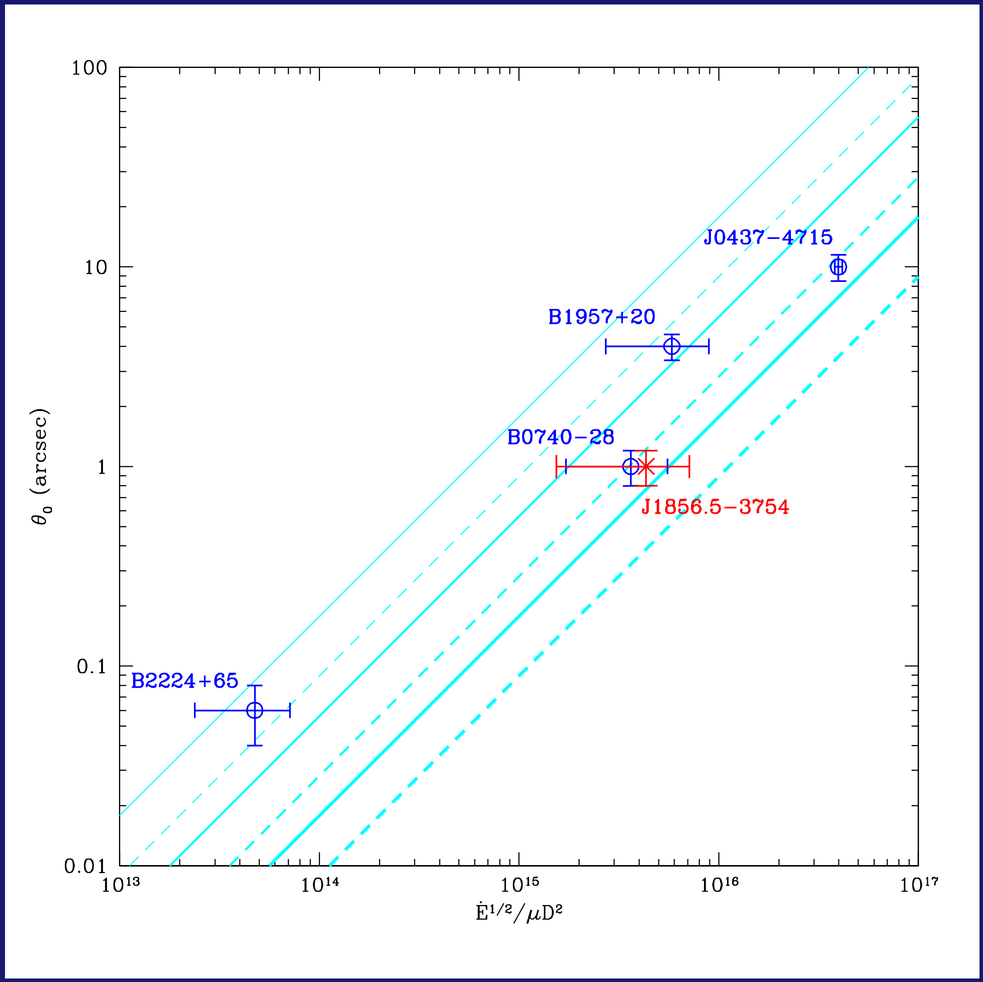
Scaling for Bow Shock Nebulae

Measure the stand-off angle for Hα bow shocks: test scaling.

$$R_0 = \sqrt{\frac{\dot{E}}{4\pi c \rho_a v_*^2}} \quad \Rightarrow \quad \theta_0 = 56.3\,\mathrm{mas}\left(\frac{\sin^2 i}{n_A^{1/2}}\right)\left(\frac{\dot{E}_{33}^{1/2}}{\mu_{100} D_{\mathrm{kpc}}^2}\right).$$

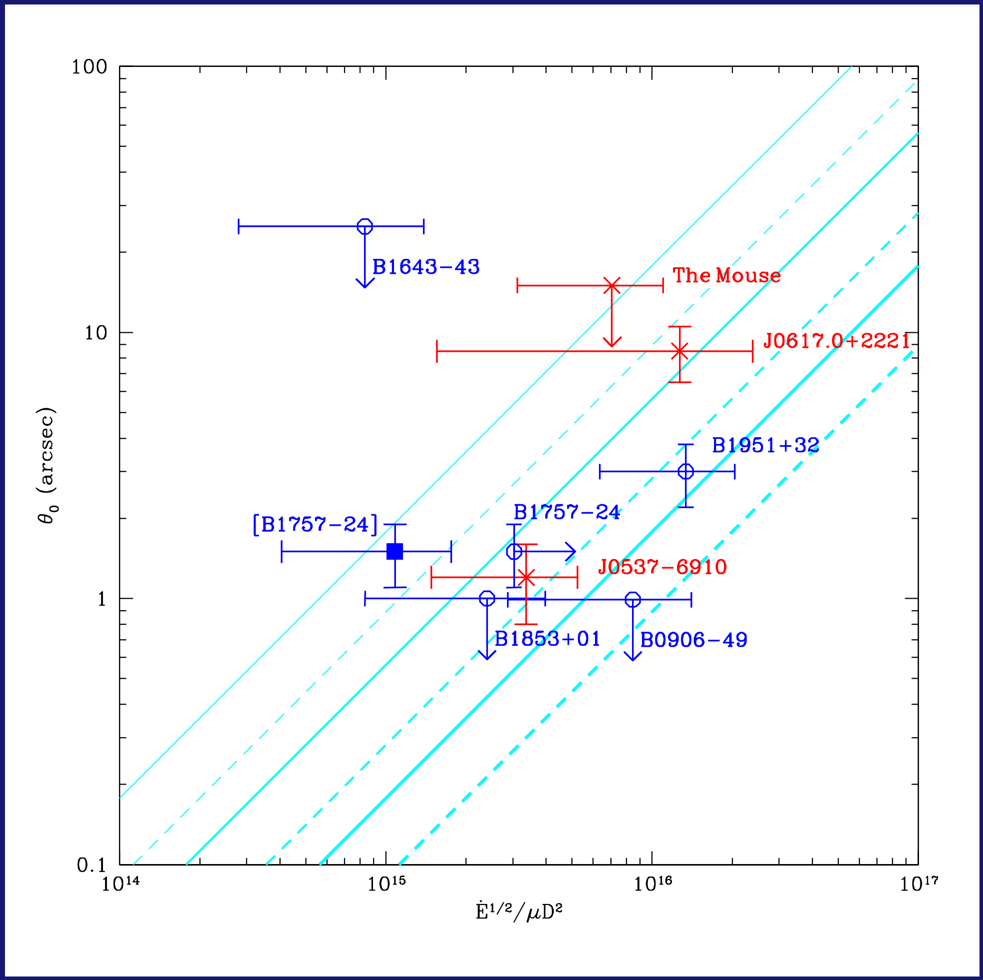
($\sin i$ term due to projection effects $\Rightarrow$ upper limits on ρ_a)

Scaling for Hα Bow Shocks



Lines of constant number density $n_A =$ 0.01, 0.1, 1.0 cm^{-3} (thinnest to thickest lines) for inclination to the line of sight $i = 90°$ (solid lines) and $i = 45°$ (dashed lines).

Scaling for Radio/X-ray Bow Shocks



As before, lines of constant $n_A = 0.01, 0.1, 1.0$ cm^{-3}, for $i = 90°$ and $45°$.

To get meaningful constraints on the ISM density and system energetics, we need *better measurements of the distance and velocity*.

So, What's Next?

With the VLBA, astrometric precision has improved by an order of magnitude: parallaxes to 2 kpc.

So, What's Next?

With the VLBA, astrometric precision has improved by an order of magnitude: parallaxes to 2 kpc.

In future:

- New pulsars from pulsar searches.
- More pulsar parallaxes and proper motions: $\sim$20 exist; we are on our way to doubling the sample.

So, What's Next?

With the VLBA, astrometric precision has improved by an order of magnitude: parallaxes to 2 kpc.

In future:

- New pulsars from pulsar searches.
- More pulsar parallaxes and proper motions:
$\sim$20 exist; we are on our way to doubling the sample.
- Follow-up on interesting objects:
  Palomar, Magellan, VLA, Chandra,
  [Your Favorite Telescope Here].

$\Rightarrow$ Multi-wavelength observations hold the key to future surprises.

Collaborators and Acknowledgements:

Jim Cordes, Wouter Vlemmings (Cornell)
Miller Goss, Walter Brisken (NRAO)
Joe Lazio (NRL), Zaven Arzoumanian (NASA GSFC)
Stephen Thorsett (UCSC), Don Backer (UC Berkeley)
Ed Fomalont, John Benson, Mark McKinnon (NRAO)
Andrew Lyne, Michael Kramer (Jodrell)

and many others ...

Pulsar Astrometry:
http://www.astro.cornell.edu/~shami/psrvlb/