Probing Pulsar Winds With X-rays

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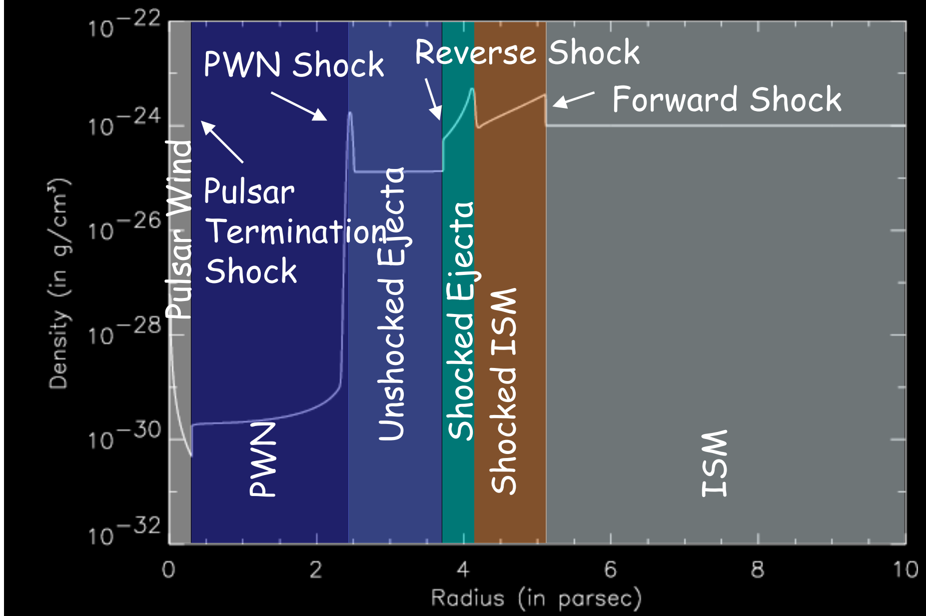
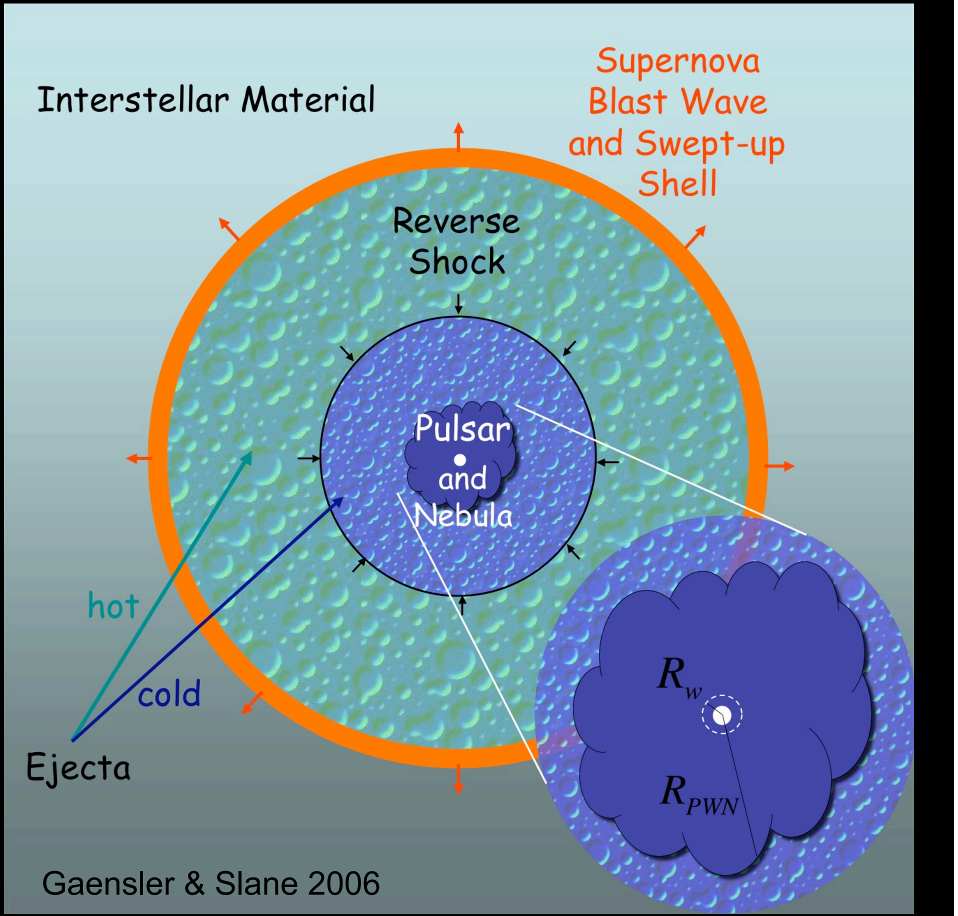
Chandra Fellows Symposium 2008

PWNe and Their SNRs

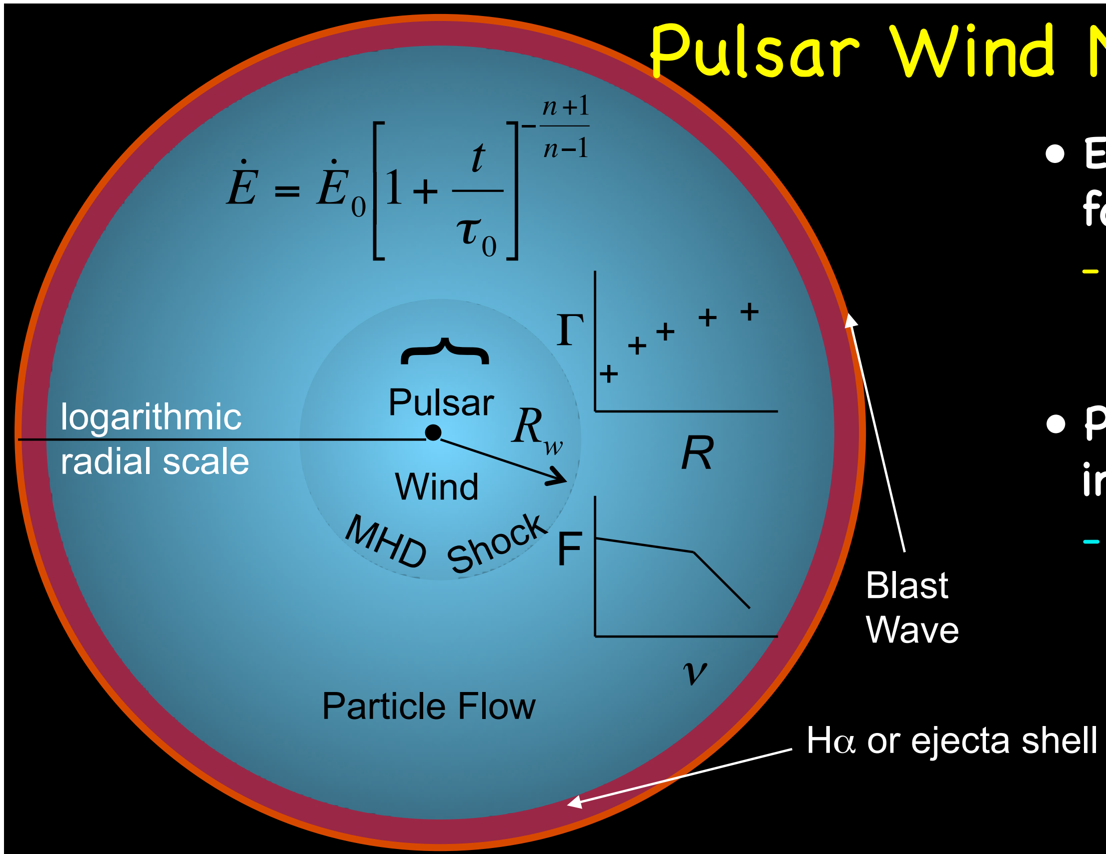




Gaensler & Slane 2006

- Pulsar Wind
  - sweeps up ejecta; shock decelerates flow, accelerates particles; PWN forms
- Supernova Remnant
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN; particles accelerated at forward shock generate magnetic turbulence; other particles scatter off this and receive additional acceleration

Pulsar Wind Nebulae



$$\dot{E} = \dot{E}_0\left[1+\frac{t}{\tau_0}\right]^{-\frac{n+1}{n-1}}$$

- Expansion boundary condition at R_w forces wind termination shock at R_N
  - wind goes from $v \approx c/\sqrt{3}$ inside R_w to $v \approx R_N/t$ at outer boundary
- Pulsar wind is confined by pressure in nebula
  - wind termination shock

$$R_w = \left[\frac{\dot{E}}{4\pi c P_N}\right]^{1/2}$$

obtain by integrating radio spectrum

- Pulsar accelerates particle wind
  - wind inflates bubble of particles and magnetic flux
  - particle flow in B-field creates synchrotron nebula
  - spectral break at $\nu_{br} \approx 10^{21} B_{\mu G}^{-3} t_3^{-2}$ Hz where synchrotron lifetime of particles equals SNR age
  - radial spectral variation from burn-off of high energy particles
- Observations resolve the termination shock region in some PWNe
  - spin-down of pulsar and broadband spectrum of nebula place constraints on the structure and evolution of the PWN

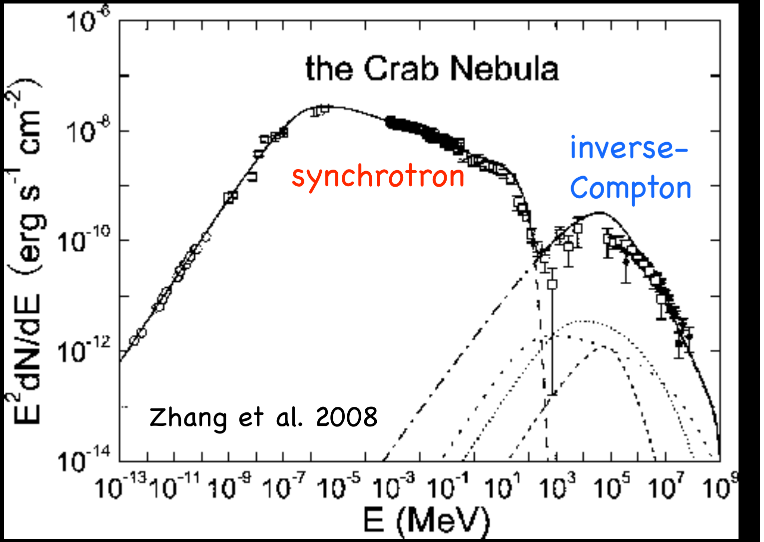
Broadband Emission from PWNe

- Spin-down power is injected into the PWN at a time-dependent rate

$$L(t) = L_0 \left[1 + \frac{(n-1)P_0^2 L_0 t}{4\pi^2 I}\right]^{-(n+1)/(n-1)}$$

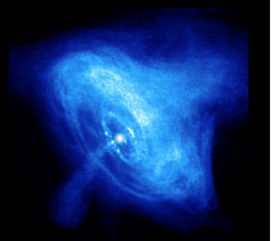
- Based on studies of Crab Nebula, there appear to be two populations – relic radio-emitting electrons and electrons injected in wind (Atoyan & Aharonian 1996)

$$Q(E_e, t) = \begin{cases} Q_0(t)(E_e/E_b)^{-\alpha_1}, & \text{if } E_e < E_b \\ Q_0(t)(E_e/E_b)^{-\alpha_2}, & \text{if } E_e \geq E_b \end{cases}$$



Zhang et al. 2008

- Get associated synchrotron and IC emission from electron population, and some assumed B field (e.g. Venter & dE Jager 2006

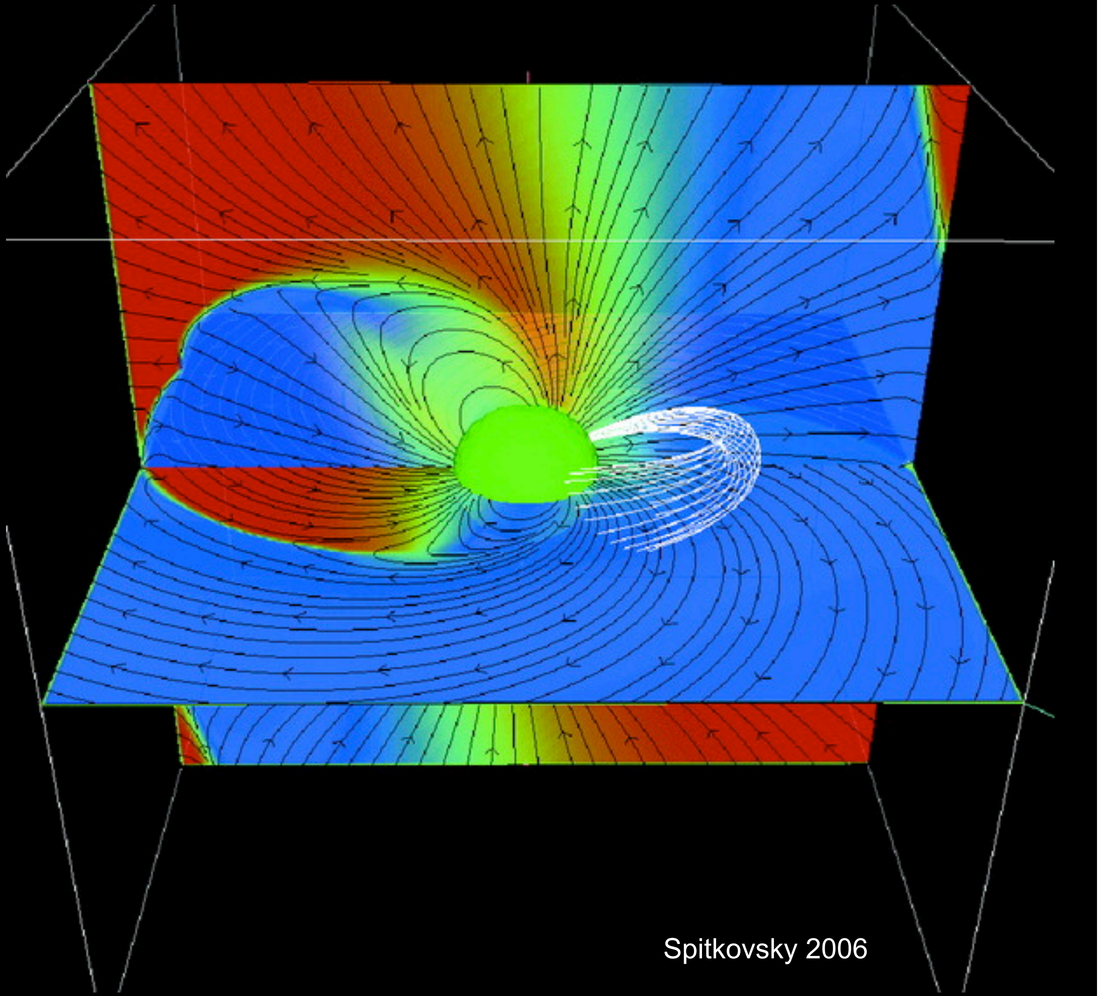


The Pulsar Wind

- Oblique rotator model for pulsar produces a toroidal field structure in the equatorial zone
  - accompanied by radial particle wind

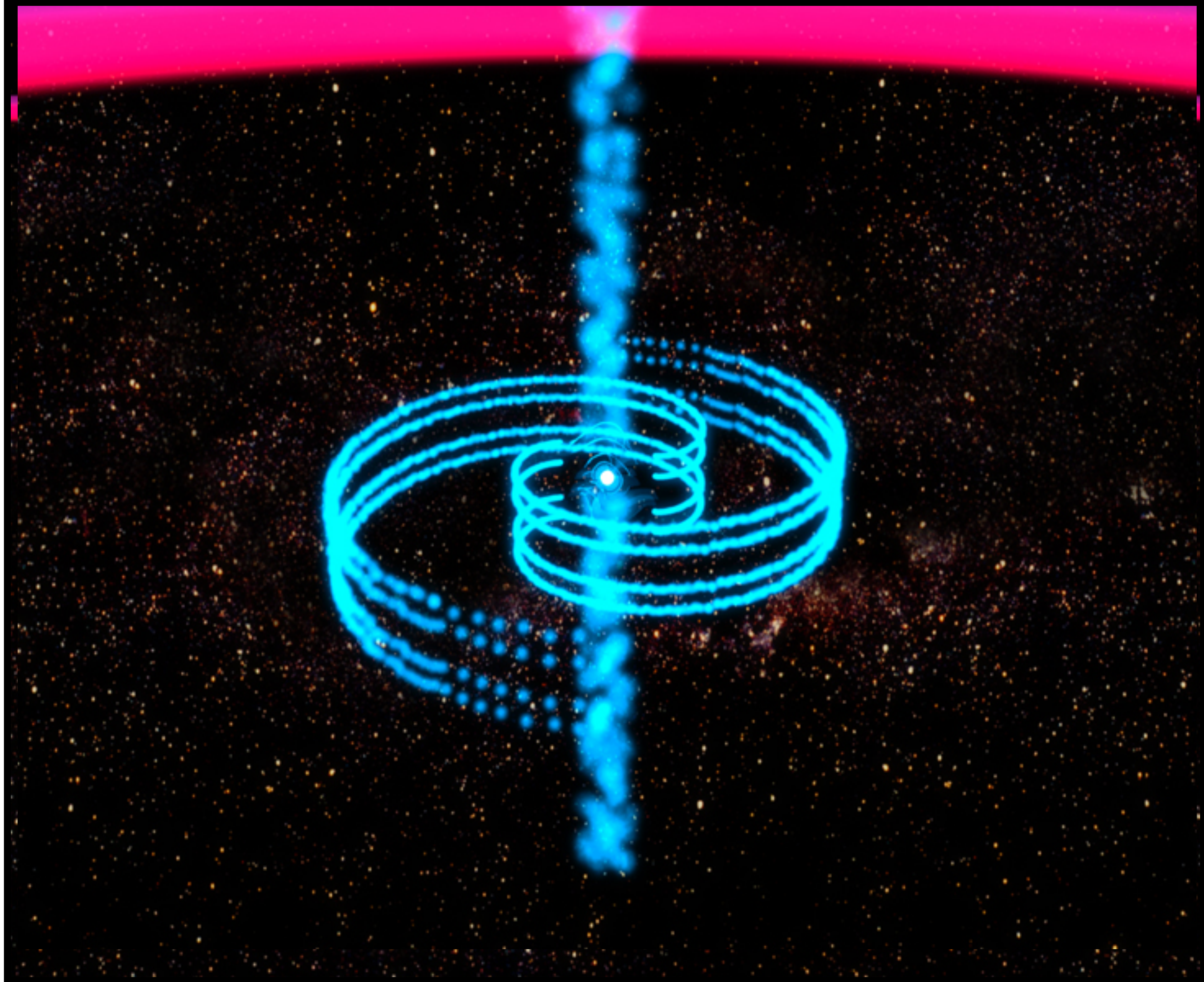
- Along equator, rotating dipole field produces alternating polarity in wound-up toroidal field
  - "striped" wind

- Near the pulsar, (outside the light cylinder) the wind is dominated by E x B, not particle flux



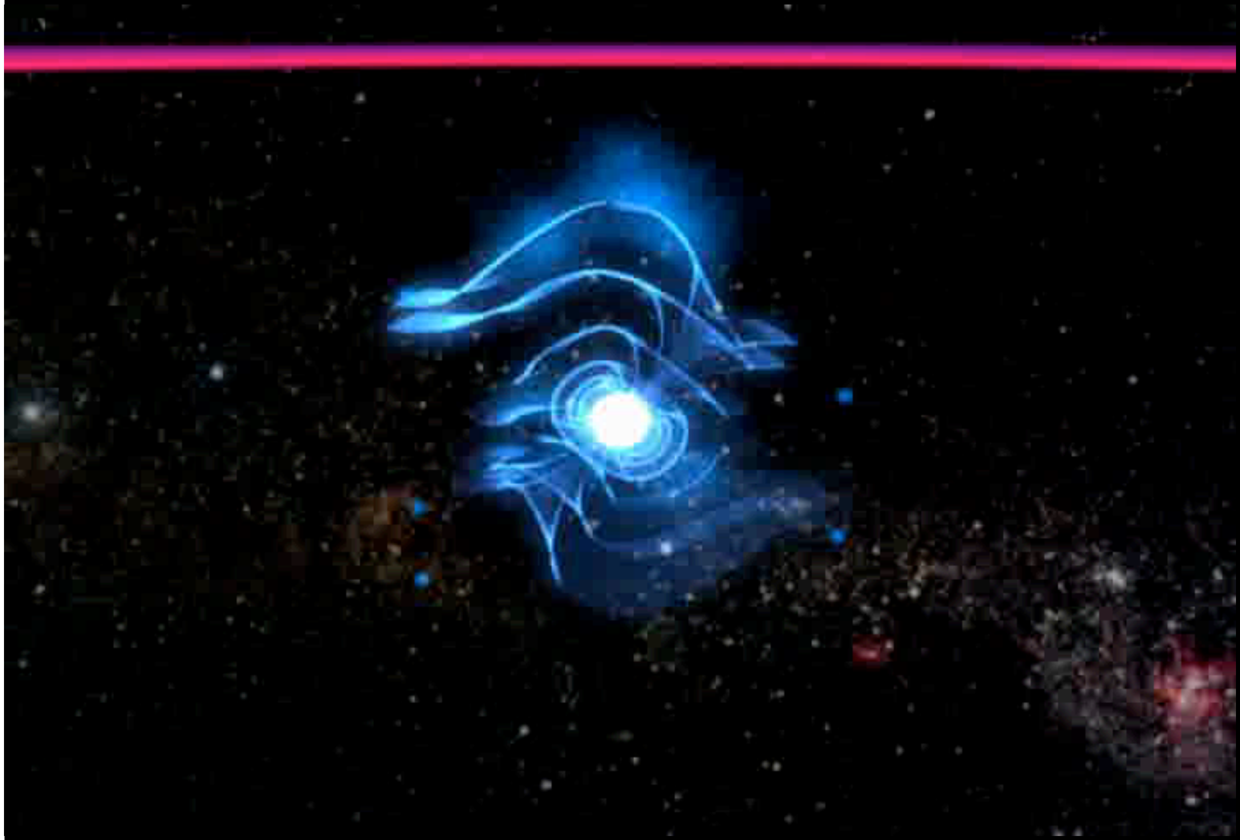
Spitkovsky 2006

The Pulsar Wind Zone



- Rotating magnetosphere generates E X B wind
  - direct particle acceleration as well, yielding ~10^4 Edot (e.g. Michel 1969; Cheng, Ho, & Ruderman 1986)
- Magnetic polarity in wind alternates spatially
  - magnetically "striped" wind
  - does reconnection result in conversion to kinetic energy? (e.g. Coroniti 1990, Michel 1994, Lyubarsky 2003)

The Pulsar Wind Zone



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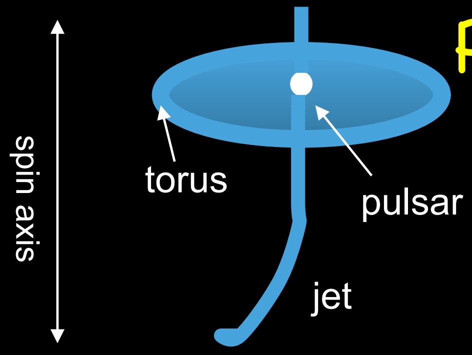
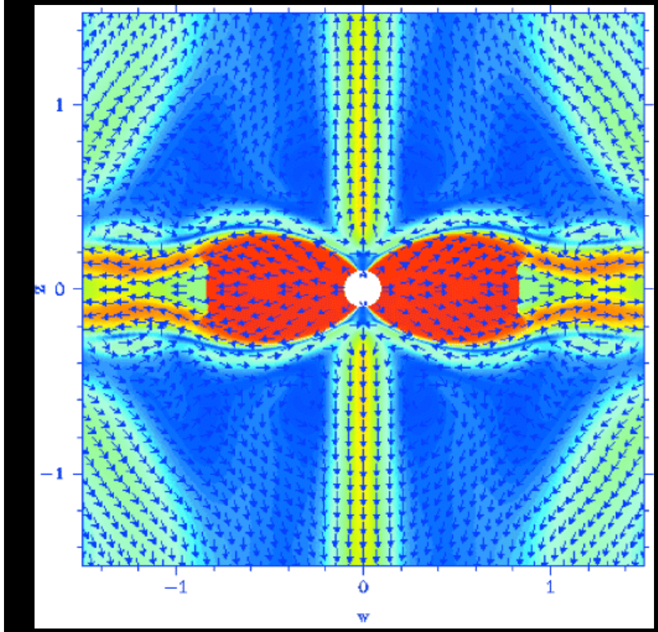
- Wind expands until ram pressure is balanced by surrounding nebula
  - flow in outer nebula restricts inner wind flow, forming pulsar wind termination shock

PWN Jet/Torus Structure





Komissarov & Lyubarsky 2003

- Poynting flux from outside pulsar light cylinder is concentrated in equatorial region due to wound-up B-field
  - termination shock radius decreases with increasing angle from equator (Lyubarsky 2002)
- For sufficiently high latitudes, particle flow is deflected back inward
  - collimation into jets may occur
  - asymmetric brightness profile from Doppler beaming
- Collimation is subject to kink instabilities
  - magnetic loops can be torn off near TS and expand into PWN (Begelman 1998)
  - many pulsar jets are kinked or unstable, supporting this picture

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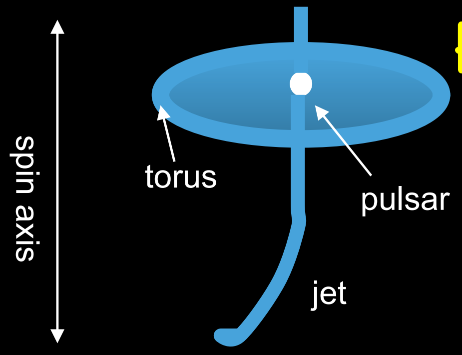

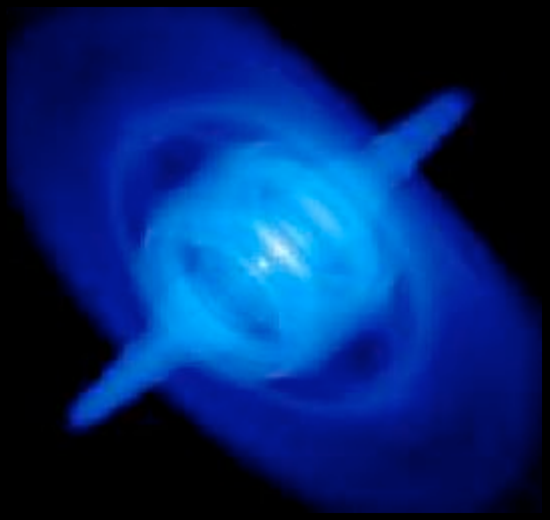

Del Zanna et al. 2006

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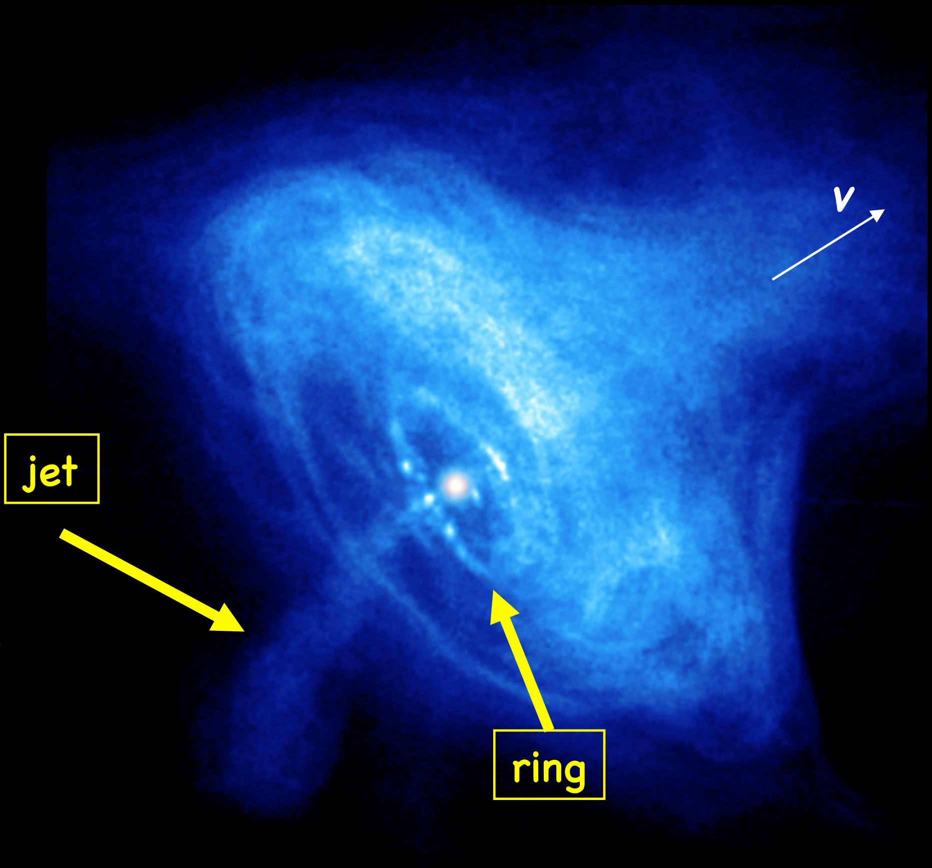
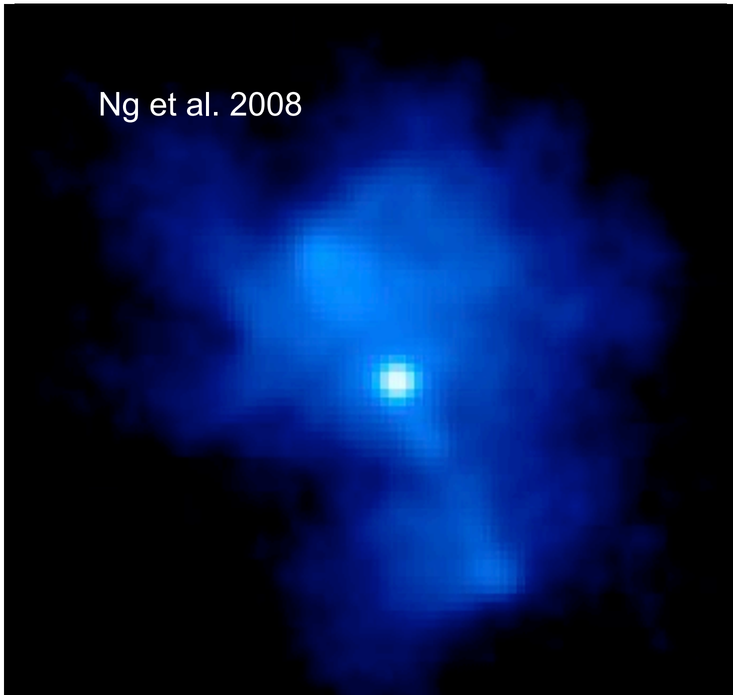
The Crab Nebula in X-rays

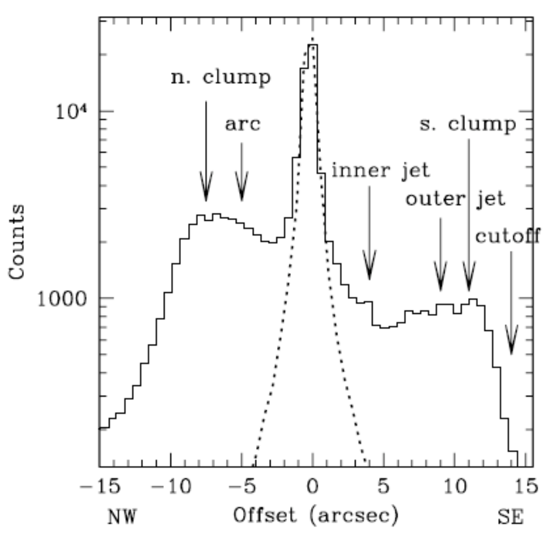
Just like the model! (Now why is that?...)

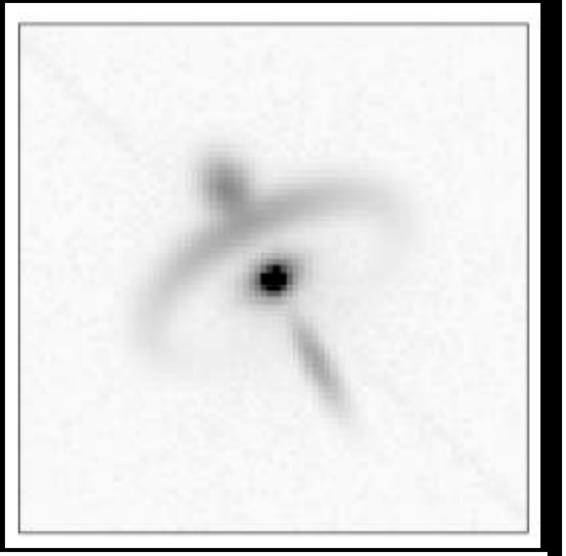
- Emission is dominated by a bright toroidal structure
  - equatorial-dominated outflow
- Inner ring of x-ray emission associated with shock wave produced by matter rushing away from neutron star
  - corresponds well with optical wisps delineating termination shock boundary
- Curved X-ray jet appears to extend all the way to the neutron star
  - faint counterjet also seen
  - jet axis ~aligned with pulsar proper motion, as with Vela Pulsar (more on that later...)

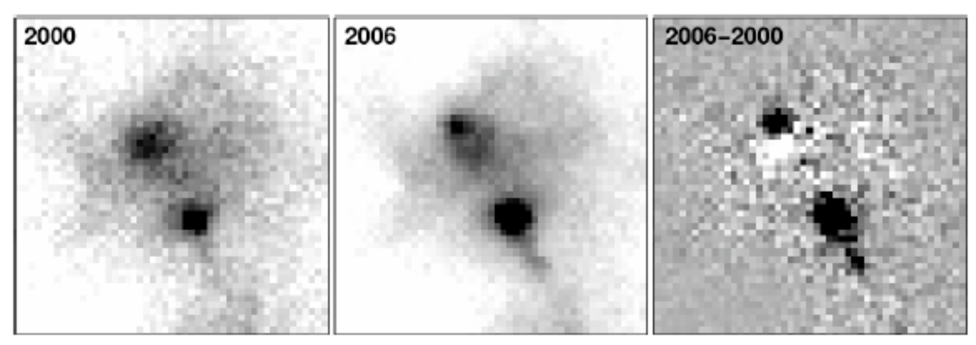


Kes 75


Ng et al. 2008





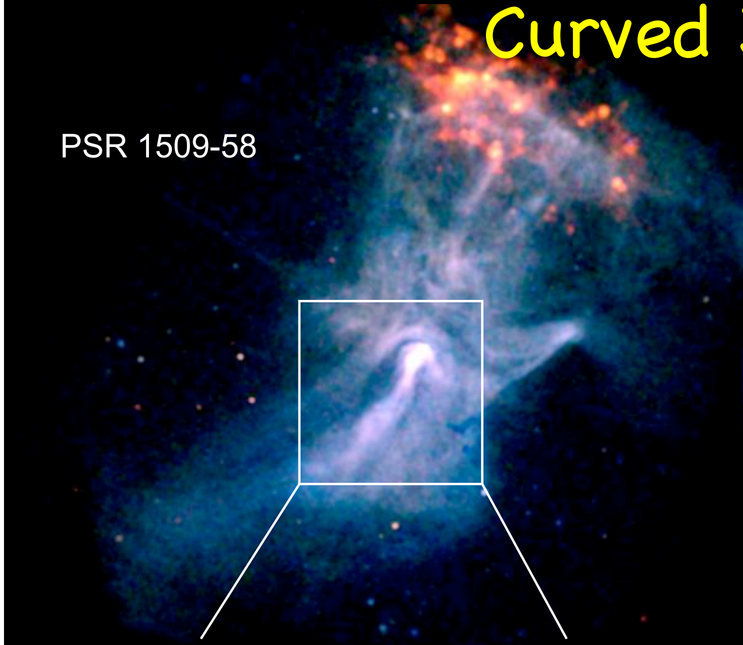


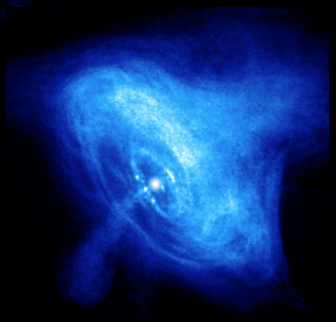
- Bright wind nebula powered by PSR J1846-0258 (dE/dt = $10^{36.9}$ erg/s)
  - jet-like structure defines rotation axis

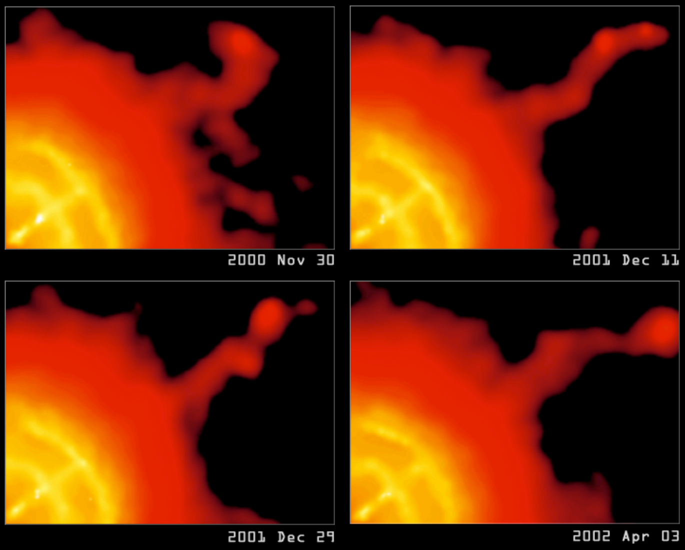
- Deep Chandra observation reveals inner/outer jet features, clump in north, and abrupt jet termination in south
  - jet spectrum is harder than surrounding regions, ➔ high-velocity (uncooled) flow
  - clumps along jet axis vary in brightness over time

Curved Jets and Instabilities

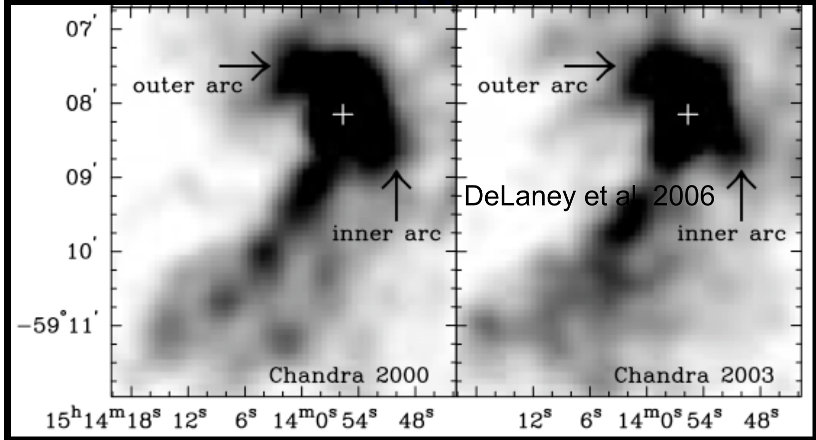
PSR 1509-58







Pavlov et al. 2003



DeLaney et al. 2006

- Jet in PSR 1509-58 is <u>curved</u>, like in Crab
  - variations in structure seen on timescale of several months (v ~ 0.5c)
- Jet in Vela is wildly unstable, showing variations on timescales of weeks to months
  - changes in morphology suggest kink or sausage instabilities (Pavlov et al. 2003)

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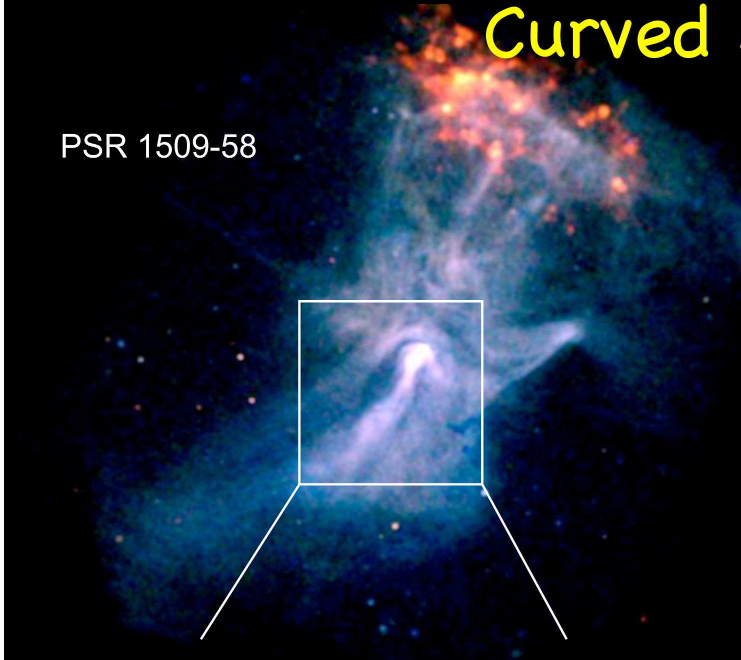
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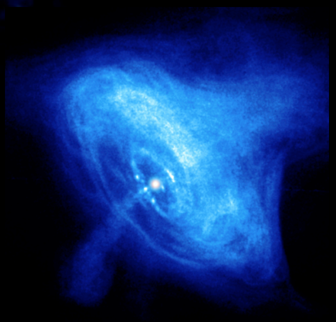

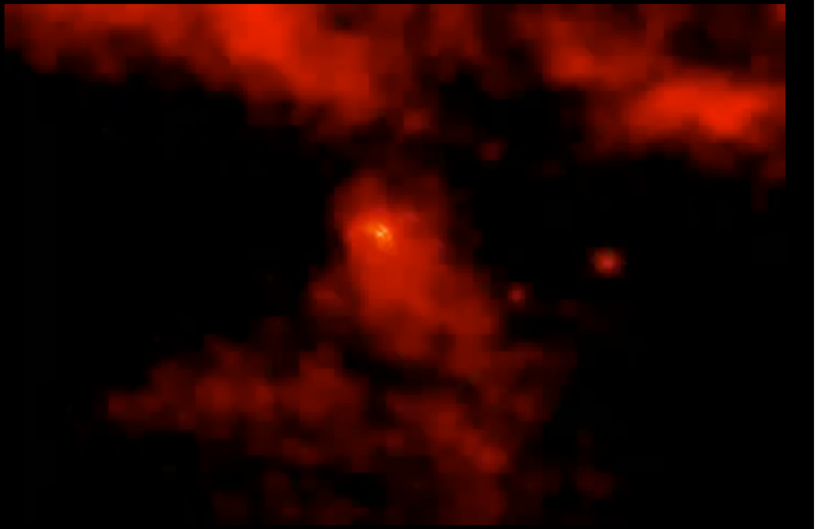
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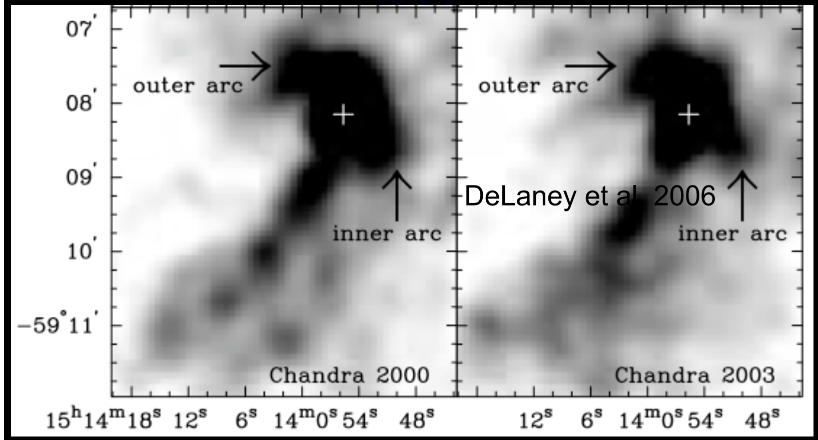
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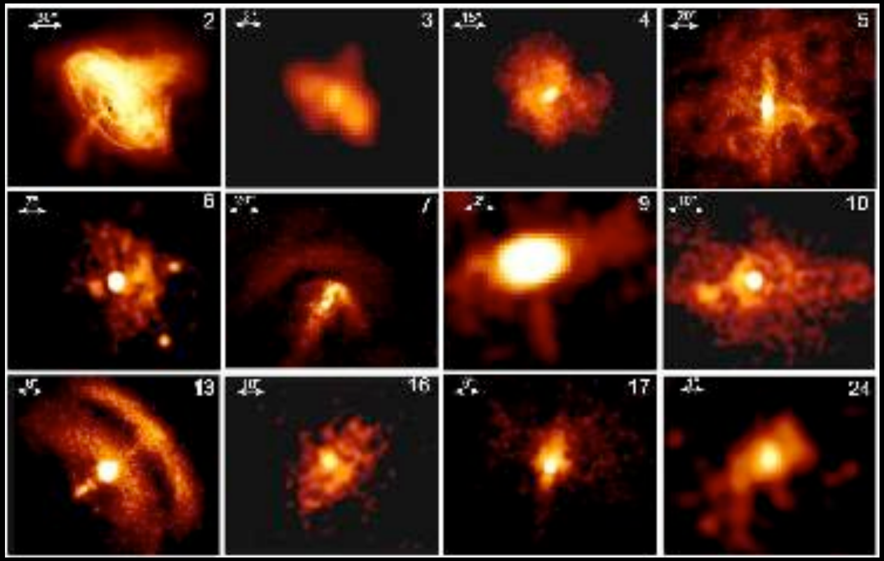
Pulsar Jets – and Lots of Them

- Jets or jet-like structures are observed for ~20 young pulsar systems
  - the more we look the more we find, though evidence is weak for some



Kargaltsev & Pavlov 2008

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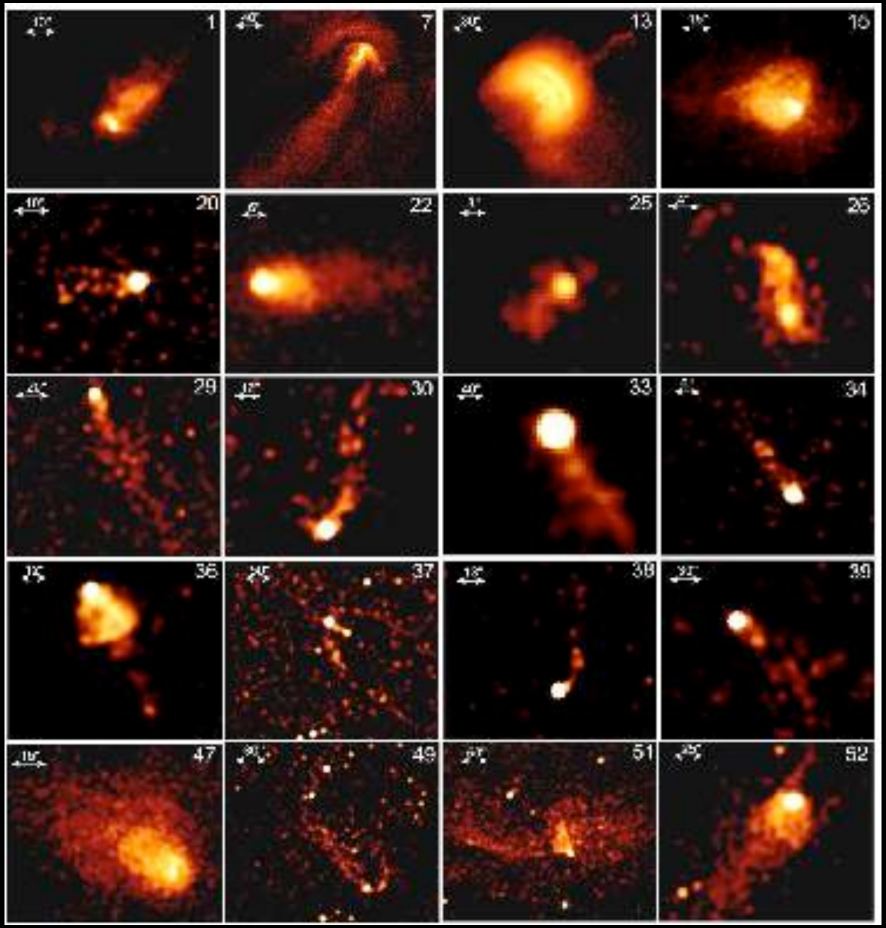
  - many more show toroidal structures or extended tails (possibly also jets)

- Sizes vary from <0.1 pc (CTA 1) to >10 pc (PSR B1509-58)
  - no strong connection with dE/dt

- Jet luminosity ranges are huge:

$$5\times10^{-7} - 6\times10^{-3}\dot{E}$$

Kargaltsev & Pavlov 2008



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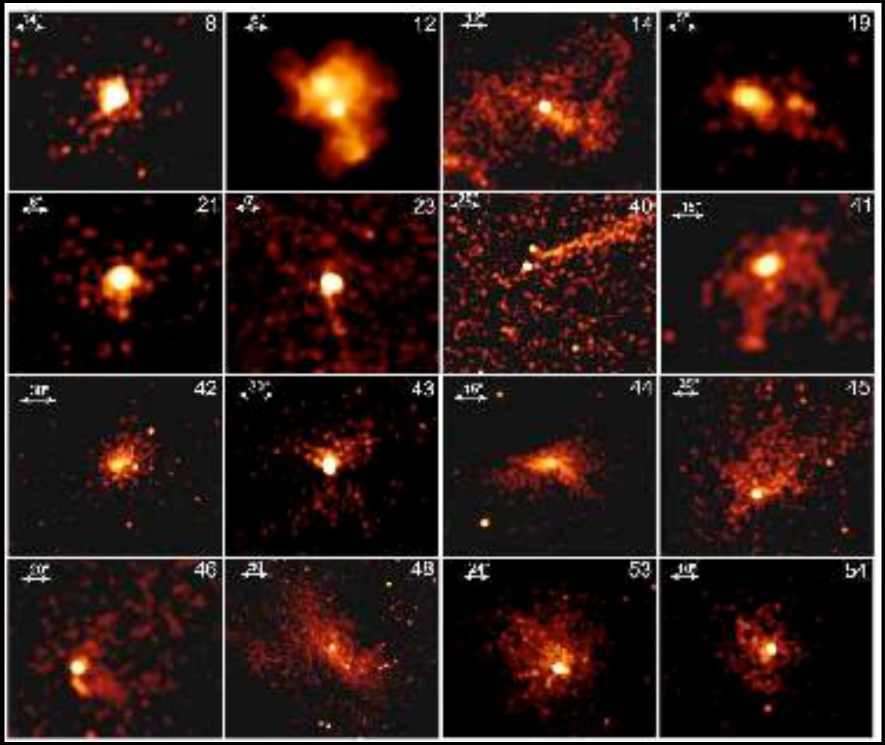

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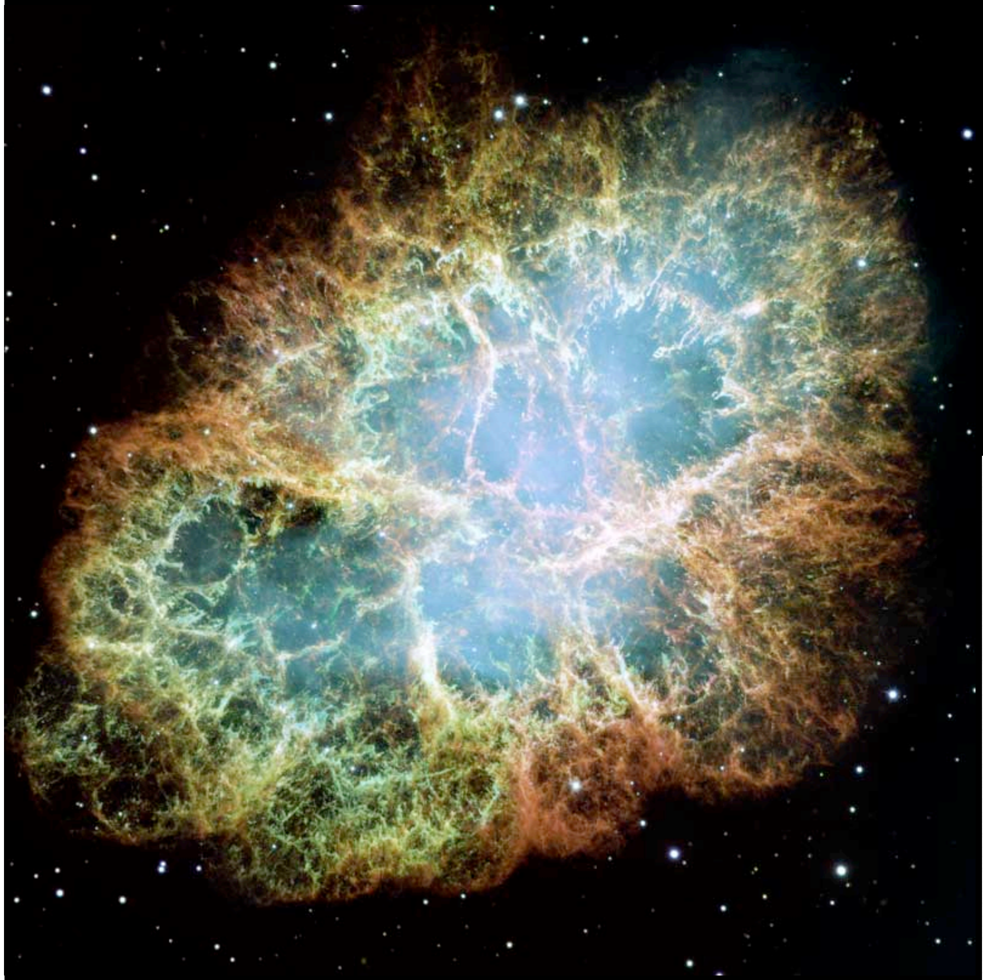
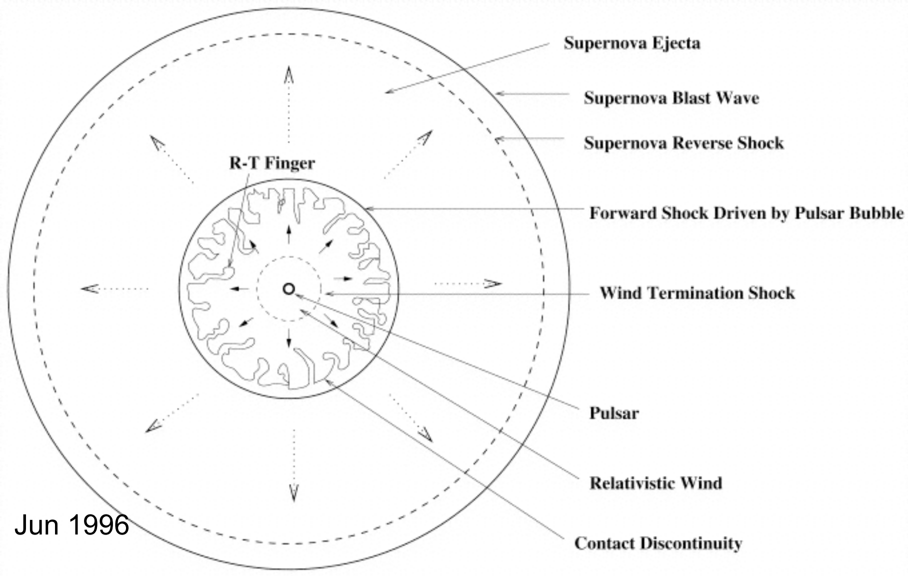
- Typical photon index Γ ~ 1.6 - 2
  - generally, uncooled synchrotron spectrum (Vela jets appears even harder)

- Where known, outflow velocities are subsonic: $v_{flow} \approx 0.1 - 0.5c$

The Surrounding Ejecta: Crab Nebula



- Optical filaments show dense ejecta
  - total mass in filaments is small; still expanding into cold ejecta
- Rayleigh-Taylor fingers produced as relativistic fluid flows past filaments
  - continuum emission appears to reside interior to filaments; <u>filamentary shell</u>



The Surrounding Ejecta: 3C 58

$$\dot{E} = I\Omega\dot{\Omega} = \dot{E}_0\left(1+\frac{t}{\tau}\right)^{-\frac{n+1}{n-1}}$$

$$\frac{dM}{dt} = 4\pi R^2 \rho_{SN}(\mathrm{v} - R/t)$$

energy input and swept-up ejecta mass

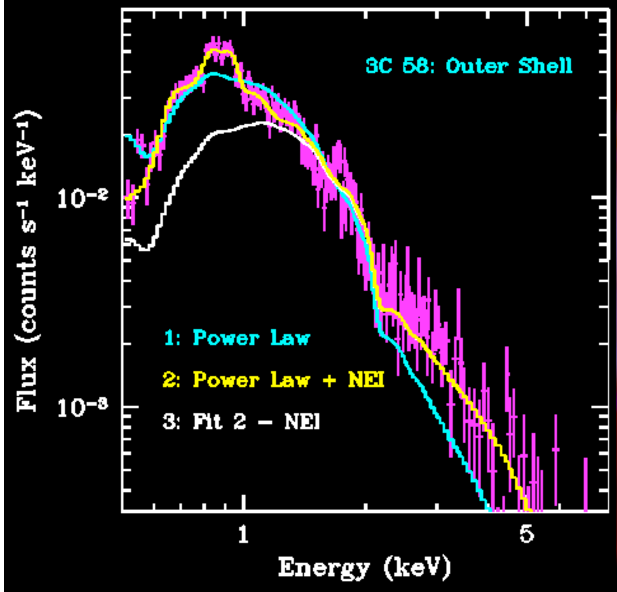
Measurements of PWN evolution and swept-up mass constrain initial spin and its evolution

$$\frac{d\left(4\pi R^2 p_i\right)}{dt} = \dot{E} - p_i 4\pi R^2 \frac{dR}{dt}$$

$$M\frac{d\mathrm{v}}{dt} = 4\pi R^2\left[p_i - \rho_{SN}\left(\mathrm{v} - R/t\right)\right]$$

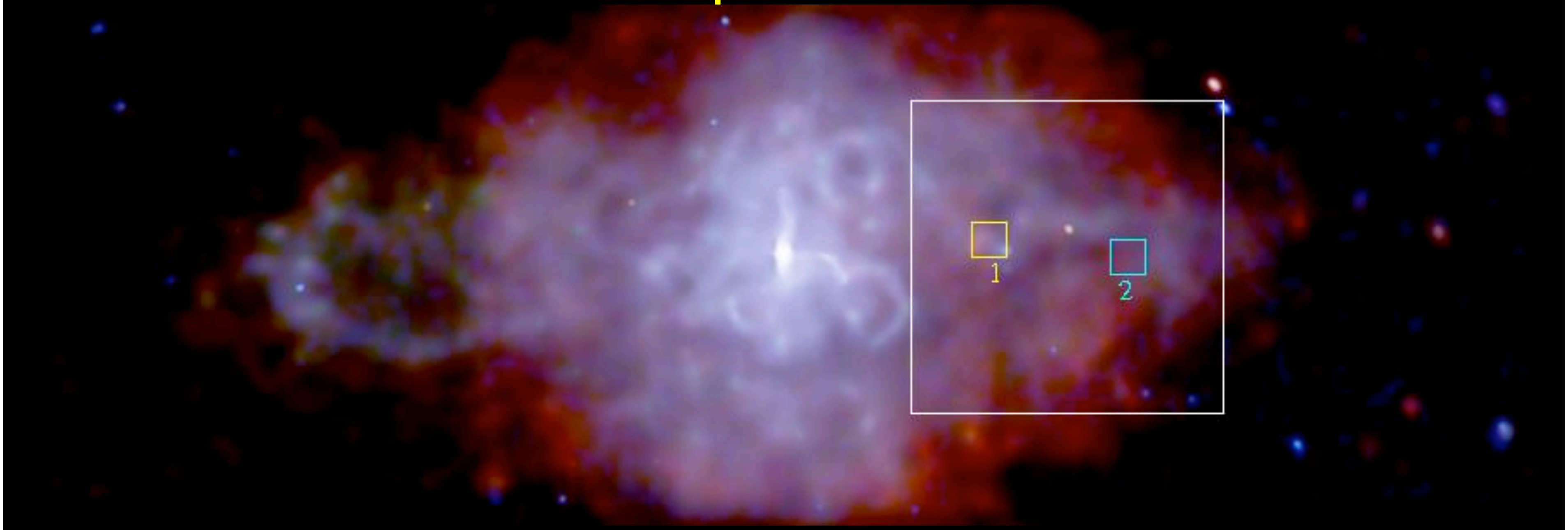
PWN evolution

The Surrounding Ejecta: 3C 58



- Chandra reveals complex structure of wind shock zone and surroundings
- Spectrum reveals ejecta shell with enhanced Ne and Mg
  - PWN expansion sweeps up and heats cold ejecta
- Mass and temperature of swept-up ejecta suggests an age of ~2400 yr and a Type IIP progenitor, similar to that for Crab (Chevalier 2005)
- Temperature appears lower than expected based on radio/optical data

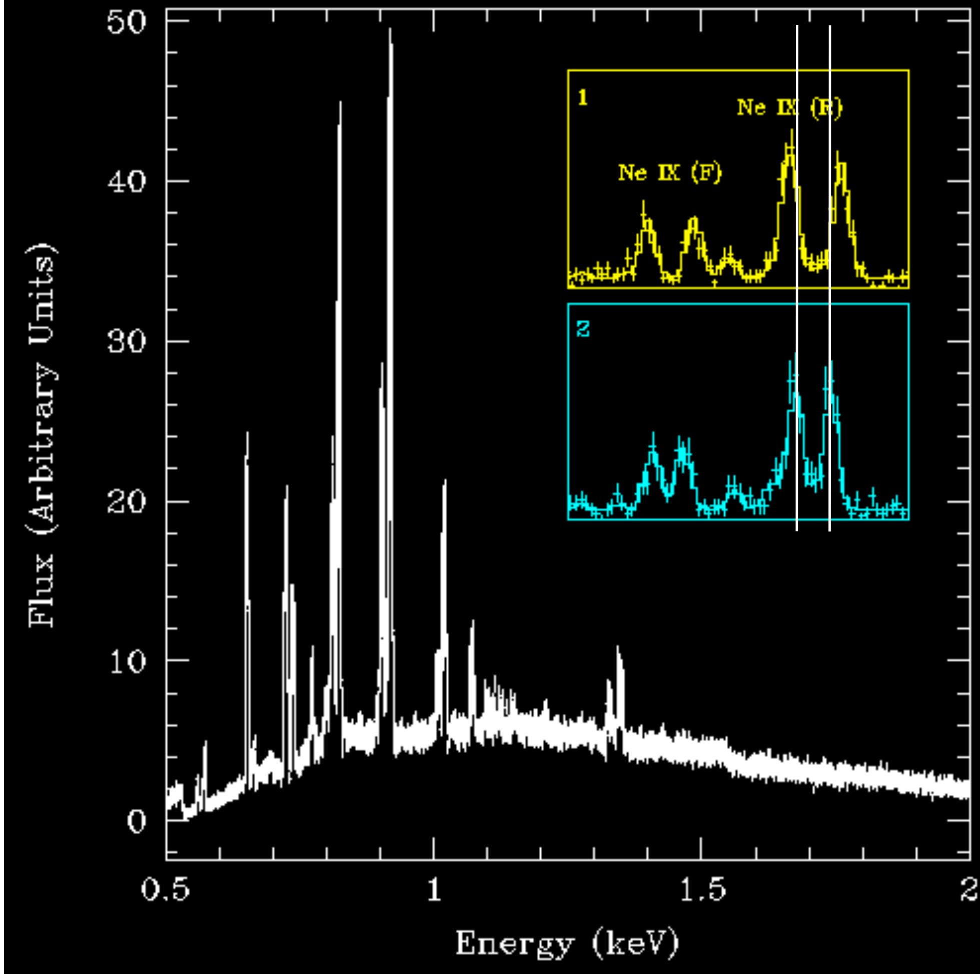
3C 58 Expansion w/ IXO

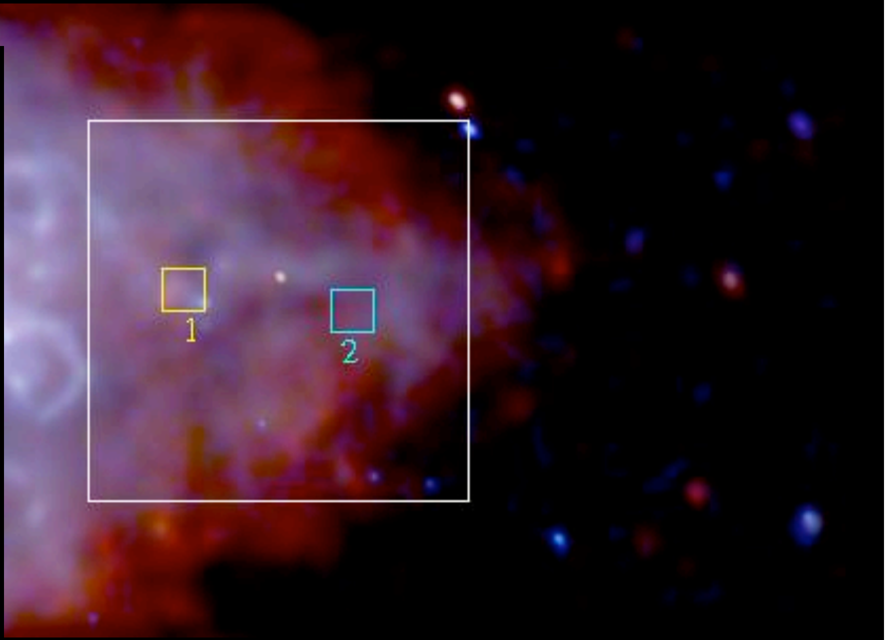


- IXO baseline gives ~16000 counts in Ne line in a ~75 ks observation.
  - thus, we will get 100 counts from this line in a resolution element 12 arcsec on a side

$$\Sigma_{Ne} = 7\times10^{-3}\,\mathrm{cnt\ ks^{-1}arcsec^{-2}}$$

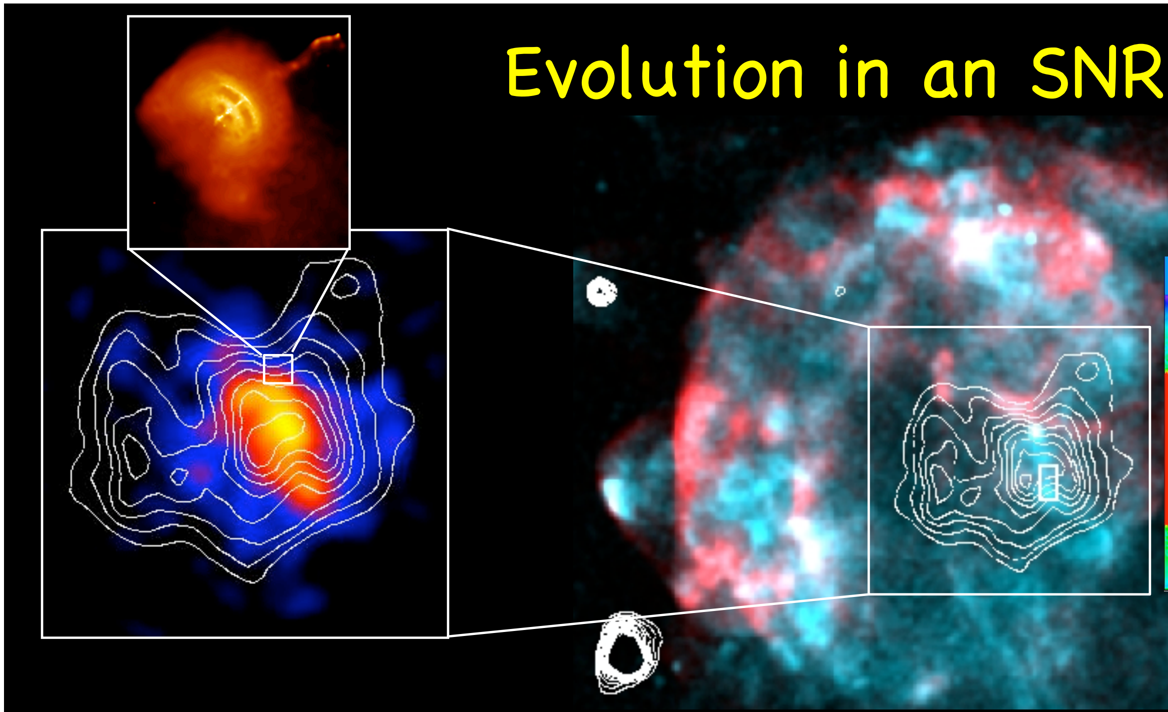
3C 58 Expansion w/ IXO

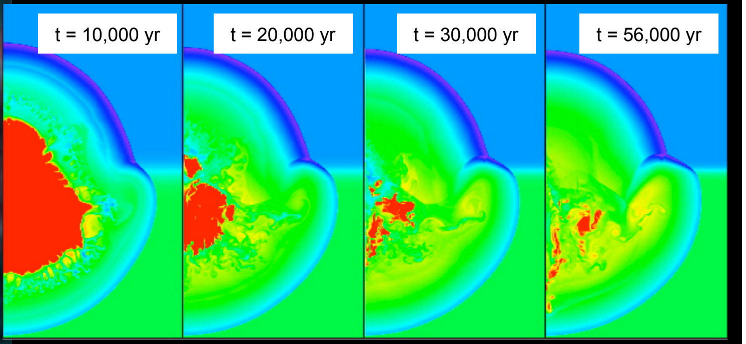




- Measure velocity broadening to determine age based on size
  - connect with evolution to determine initial spin and spindown properties
- Maximum velocities in optical are 900 km s^{-1}
  - to detect broadening we need resolution of about 2.7 eV

Evolution in an SNR: Vela X



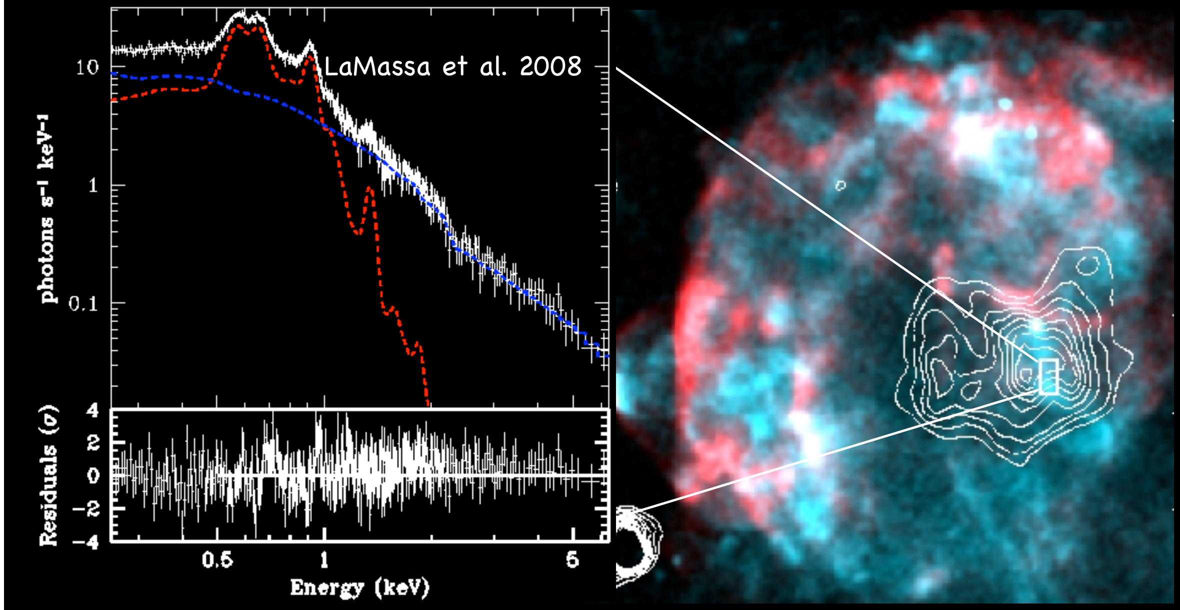


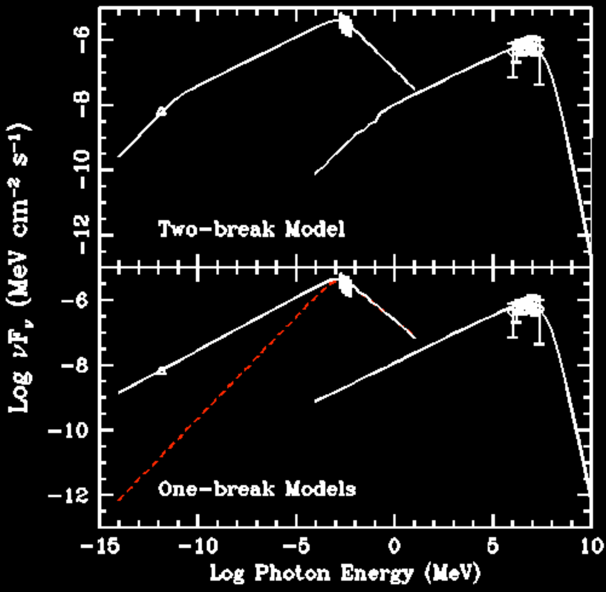
Blondin et al. 2001

- Vela X is the PWN produced by the Vela pulsar
  - located primarily south of pulsar
  - apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock

- Elongated "cocoon-like" hard X-ray structure extends southward of pulsar
  - clearly identified by HESS as an extended VHE structure
  - this is not the pulsar jet (which is known to be directed to NW); presumably the result of reverse shock interaction

Evolution in an SNR: Vela X

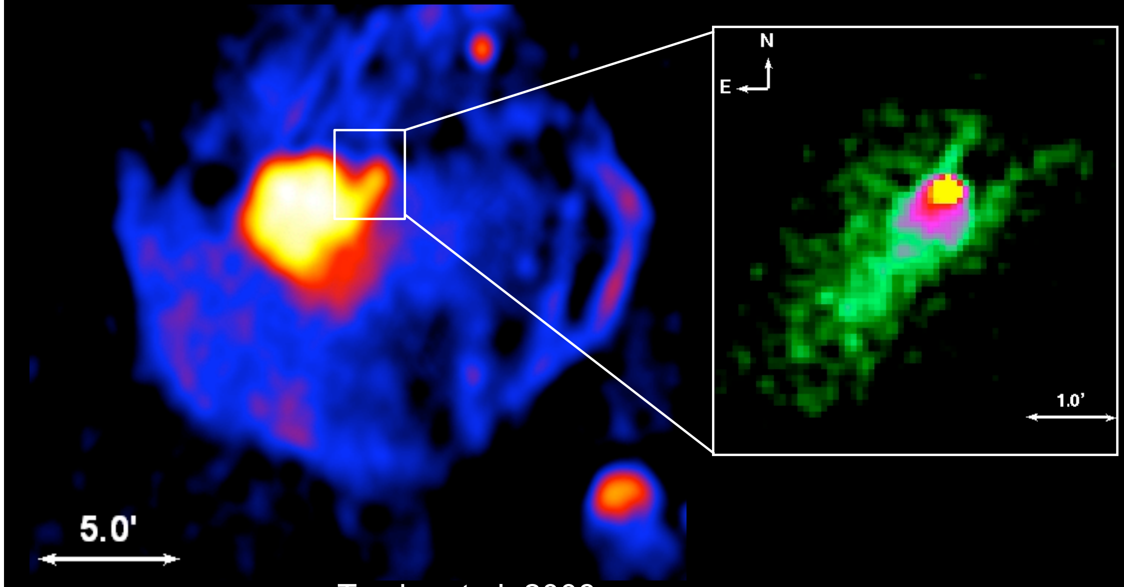

LaMassa et al. 2008



- XMM spectrum shows nonthermal <u>and</u> ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta?

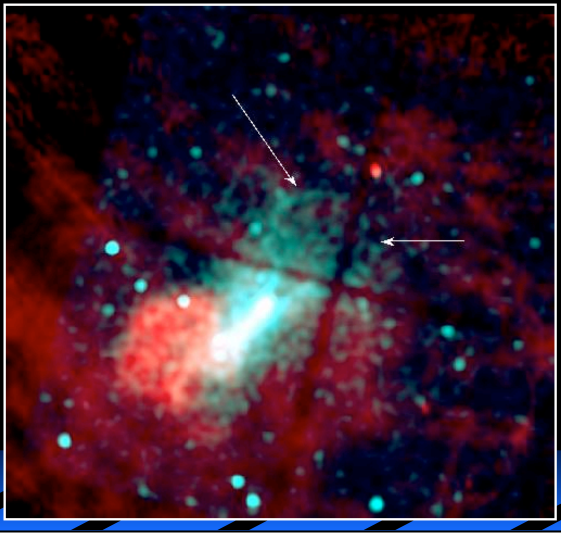
- Radio, X-ray, and γ-ray measurements appear consistent with synchrotron and I-C emission from power law particle spectrum w/ two spectral breaks
  - density derived from thermal emission 10x lower than needed for pion-production to provide observed γ-ray flux
  - <u>much larger X-ray coverage of Vela X is required to fully understand structure</u>

G327.1-1.1: Another Reverse-Shock Interaction?



Temim et al. 2008

- G327.1-1.1 is a composite SNR with a bright central nebula
  - nebula is offset from SNR center
  - "finger" of emission extends toward northwest
- X-ray observations reveal a compact source at tip of finger
  - trail of emission extends into PWN
  - L_X suggests Edot ~ $10^{37.3}$ erg s^{-1}



- Compact X-ray emission is extended; pulsar torus?
  - PWN has apparently been disturbed by SNR reverse shock, and is now re-forming around pulsar, much like Vela X
- Curious prong-like structures extend in direction opposite the relic PWN
  - these prongs appear to connect to a bubble blown by the pulsar in the SNR interior, apparently in the region recently crossed by the reverse shock

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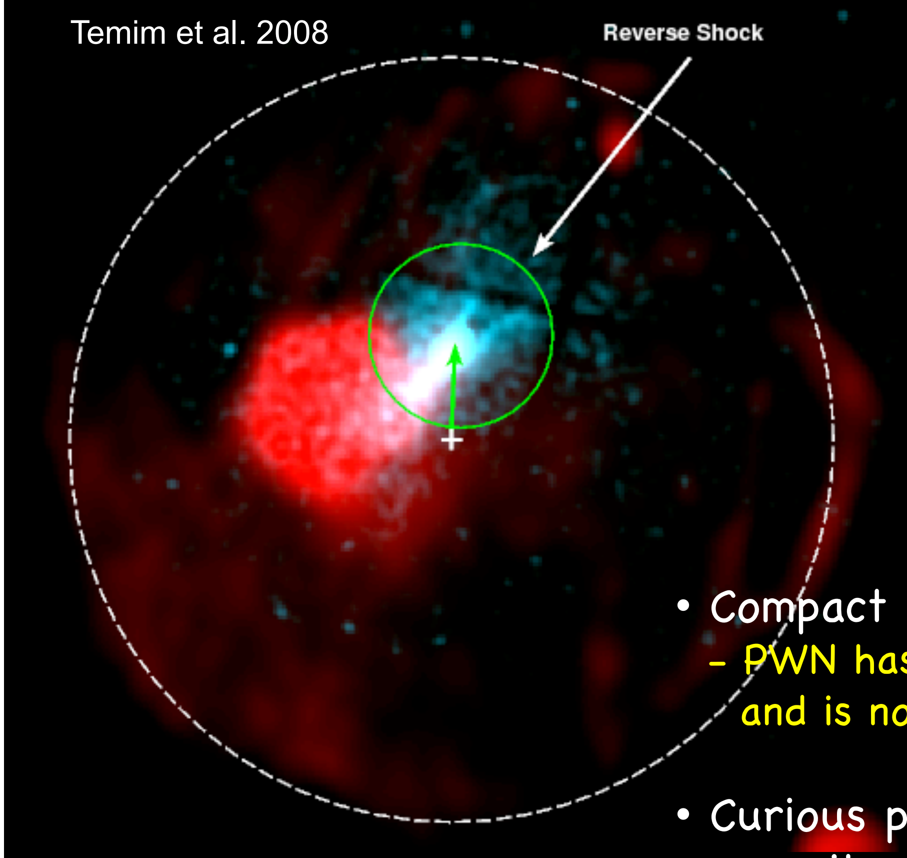
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Conclusions

- Recent X-ray observations show that jet/torus structures around pulsars are common
  - jet sizes and luminosities span a huge range; structure can be highly variable and unstable

- PWNe are reservoirs of energetic particles injected from pulsar
  - synchrotron and inverse-Compton emission places strong constraints on the underlying particle spectrum and magnetic field

- Modeling of broadband emission constrains evolution of particles and B field
  - modeling form of injection spectrum and full evolution of particles still in its infancy

- Reverse-shock interactions between SNR and PWNe distort nebula and may explain TeV sources offset from pulsars
  - multiwavelength observations needed to secure this scenario (e.g. Vela X)