Pulsar Wind Nebulae

George Pavlov & Oleg Kargaltsev

Pennsylvania State University

General outlook
Chandra results
Polarization in radio and optical
X-ray polarization

Pulsar Wind Nebulae:

- extended objects around spin-powered pulsars
- seen from radio to gamma-rays, most easily observed in radio and X-rays
- smooth, power-law-like spectra
- synchrotron emission from shocked pulsar wind

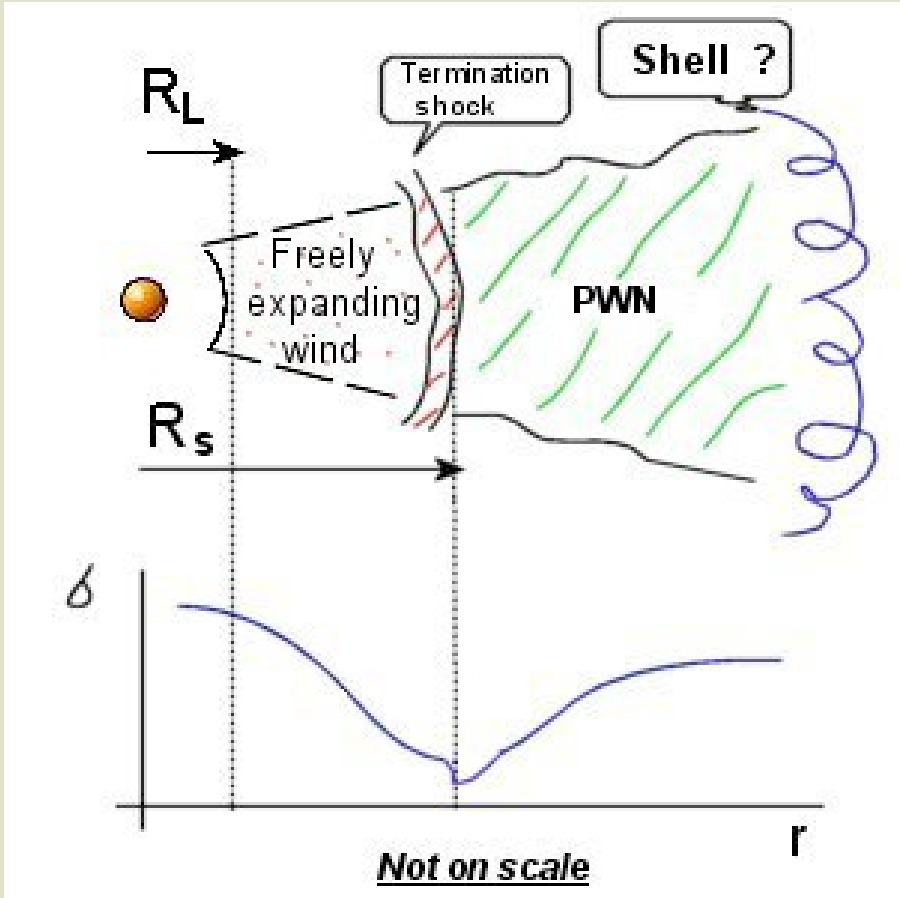
Simple model (Rees & Gunn 1974, Kennel & Coroniti 1984):

Isotropic pulsar wind, comprised of relativistic electrons/positrons and electromagnetic field, is shocked at a distance R_S where the wind pressure $Edot/(4\pi c R_S^2)$ equals pressure of the ambient medium: $R_S = (Edot/4\pi c p_{amb})^{1/2}$.

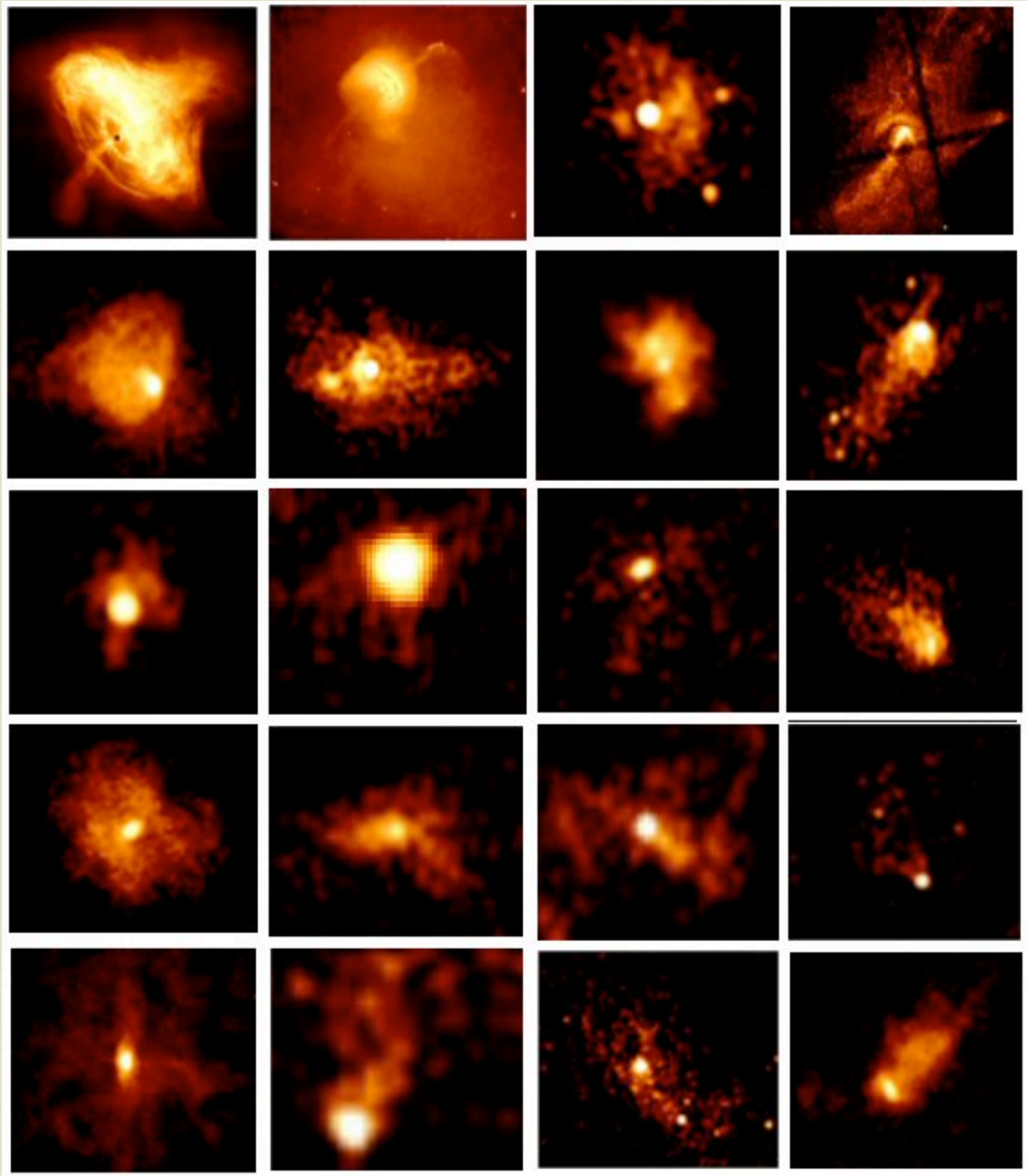
Properties of the shock and post-shock flow depend on "magnetization parameter" σ = (Poynting flux)/(KE flux) .

The shock is “strong”, and the PWN is bright, if $\sigma << 1$ before the shock. (However, $\sigma >> 1$ near the light cylinder, at $R=R_L=c/\omega$ --- “σ paradox”.)

Earlier observations are crudely consistent with this model (e.g., $\sigma \sim 0.003$ for Crab PWN), but the flow is equatorial rather than radial [$4\pi \rightarrow \Omega$;
$R_S = (Edot/4\pi c p_{amb})^{1/2} \rightarrow$
$\rightarrow R_S = (Edot/\Omega c p_{amb})^{1/2}$]

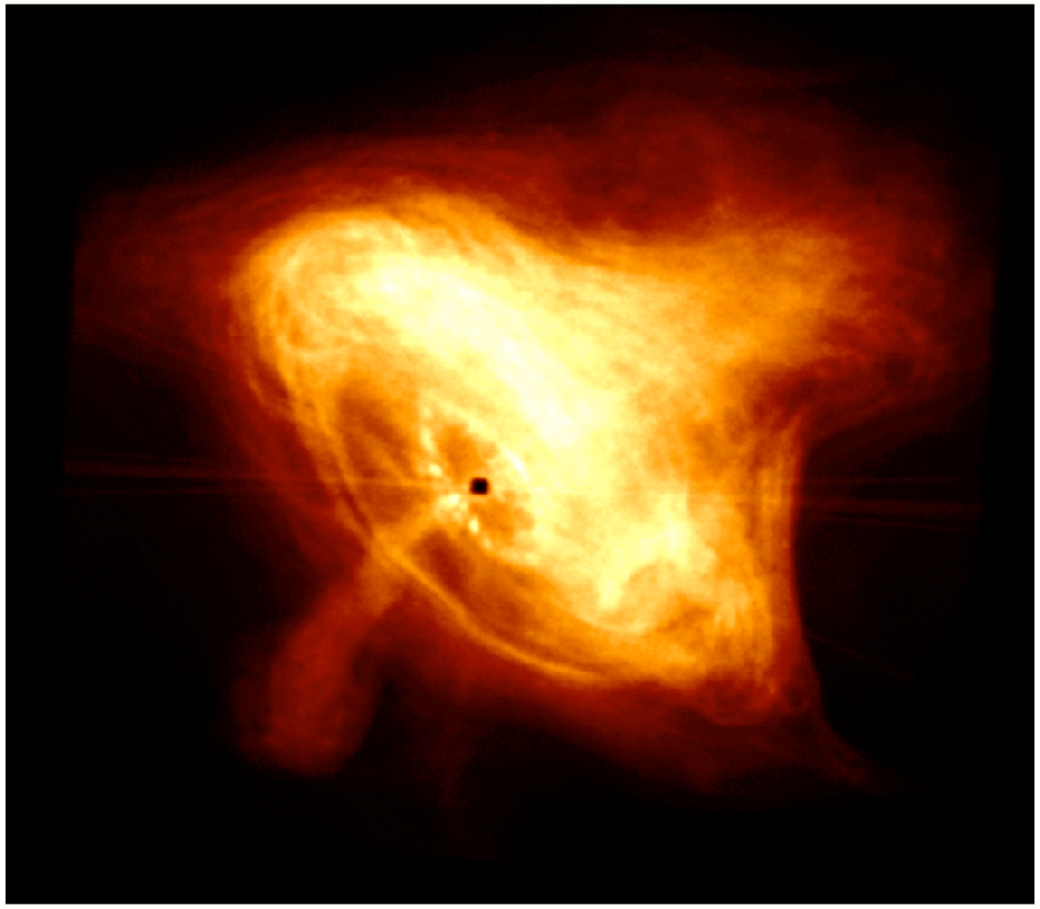


High-resolution **Chandra observations** → more complicated picture: some PWNe show ~axial symmetry, others look asymmetric



Famous example: The Crab PWN

Chandra ACIS image (Weisskopf et al 2000)



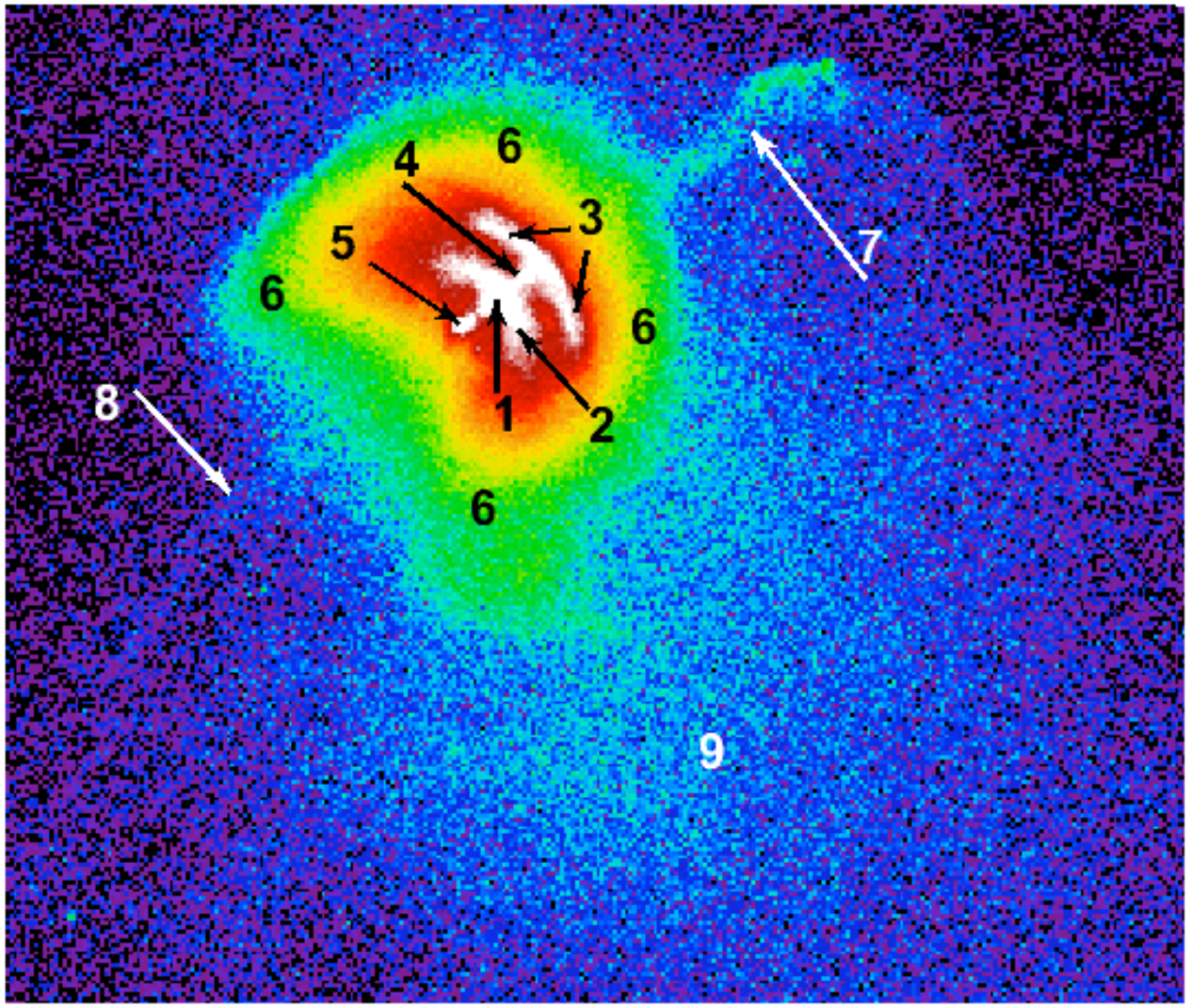
Ring(s), jets, torus, wisps…

Inner ring: termination shock

Approximate axial symmetry, around the PSR rotation axis (jet direction)

Pulsar wind is anisotropic, with polar and equatorial components

Vela PWN: Deep ACIS Image

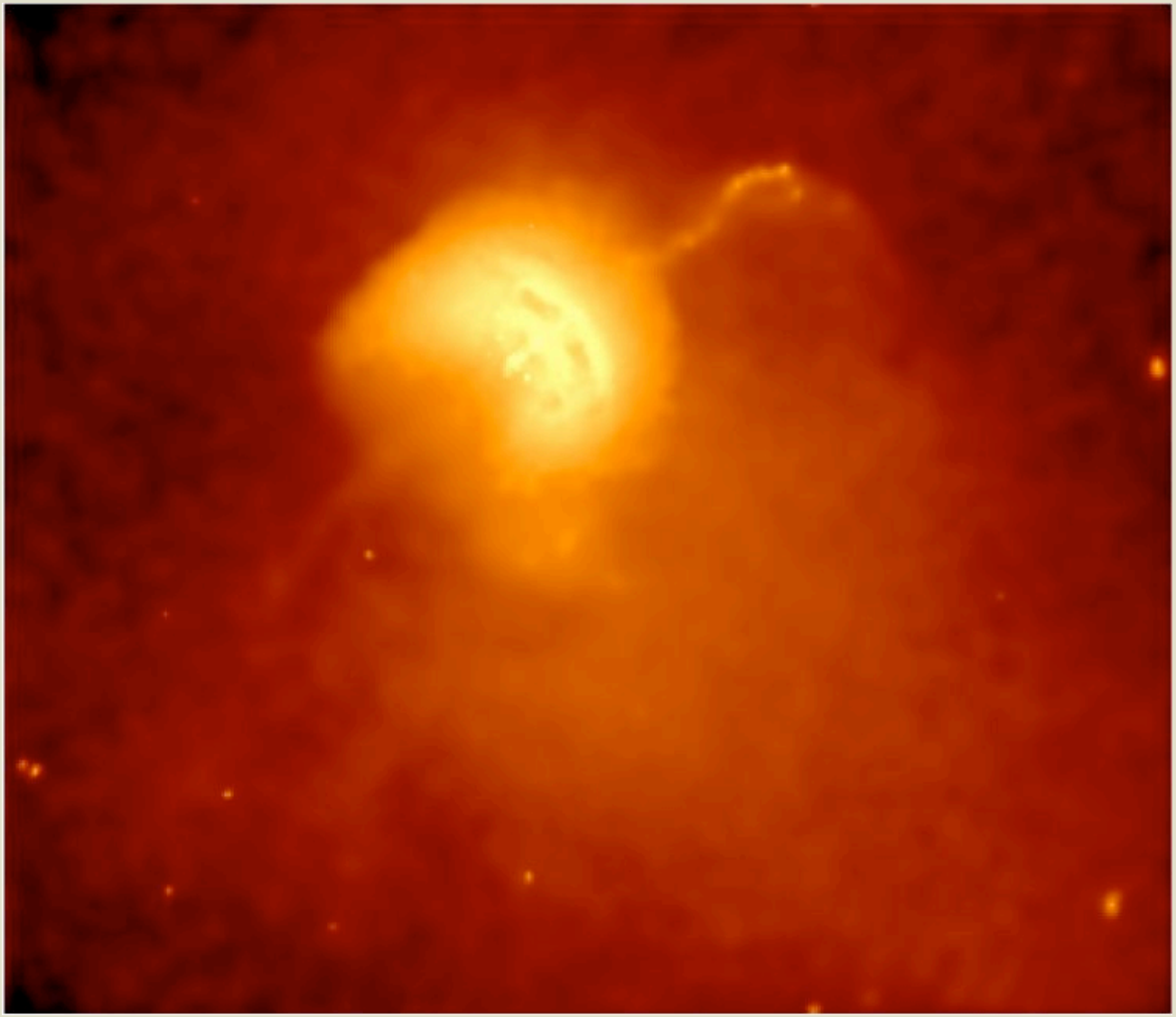


1: Vela Pulsar
2: Inner Arc
3: Outer Arc
4: Inner Jet
5: Inner Counter-jet
6: Shell
7: **Outer Jet**
8: Outer Counter-jet
9: Outer Nebula

The outer nebula is asymmetric

Vela PWN: Deep ACIS image

6’x5.5’ = 0.52pc x 0.48 pc @ d=300 pc

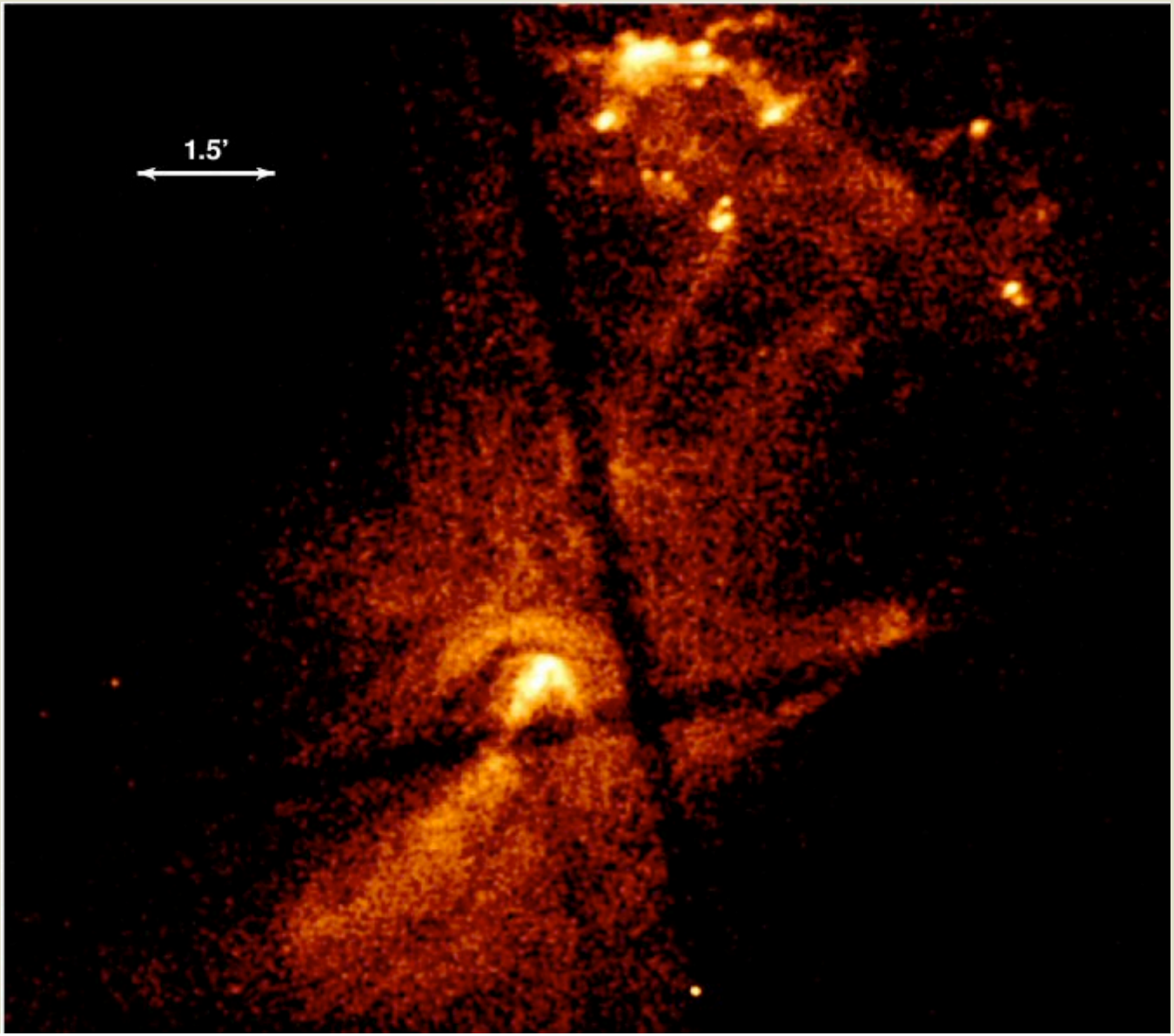


Dim outer jet along direction of proper motion and very dim outer counter-jet

Asymmetric faint nebula SW of the PSR

PWN around PSR B1509-58 in MSH 15-52 (G320.4-1.2)

1.5’ = 2.2 pc @ d=5.1 kpc



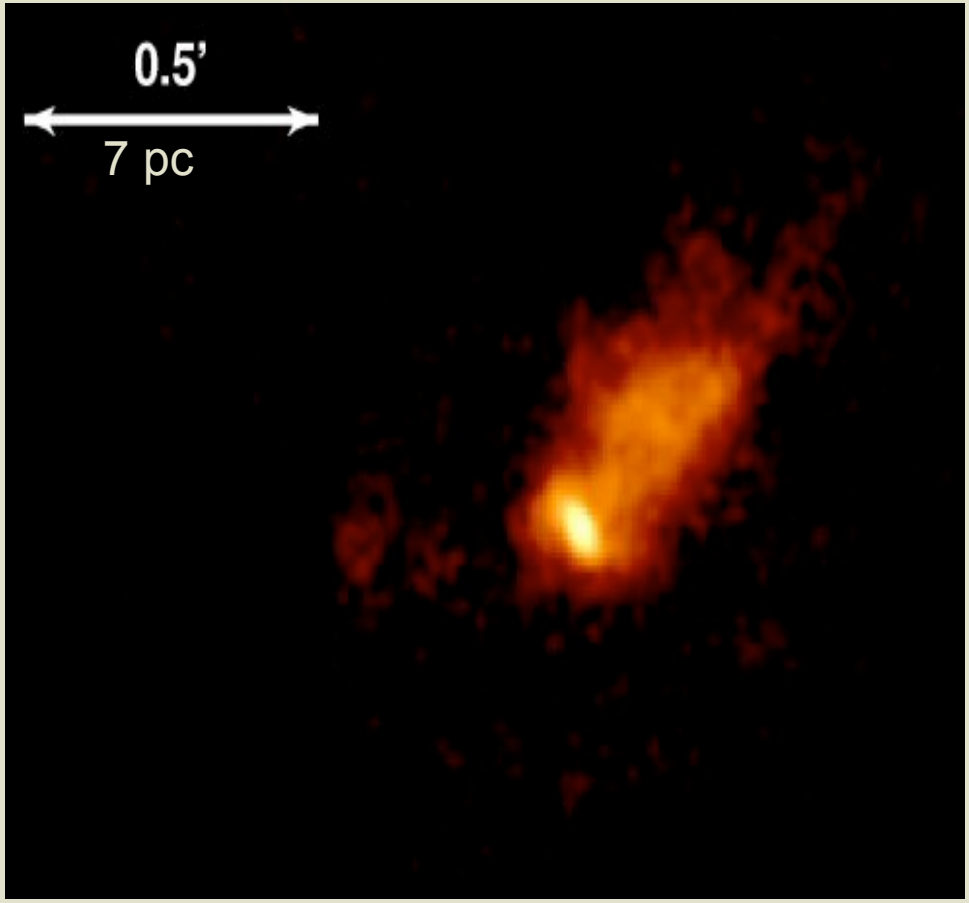
“Jelly-fish” PWN,
with a long jet
SE of PSR,
Two arc (wisps?)

RCW 89
(North of PSR)
apparently
powered by
PSR wind

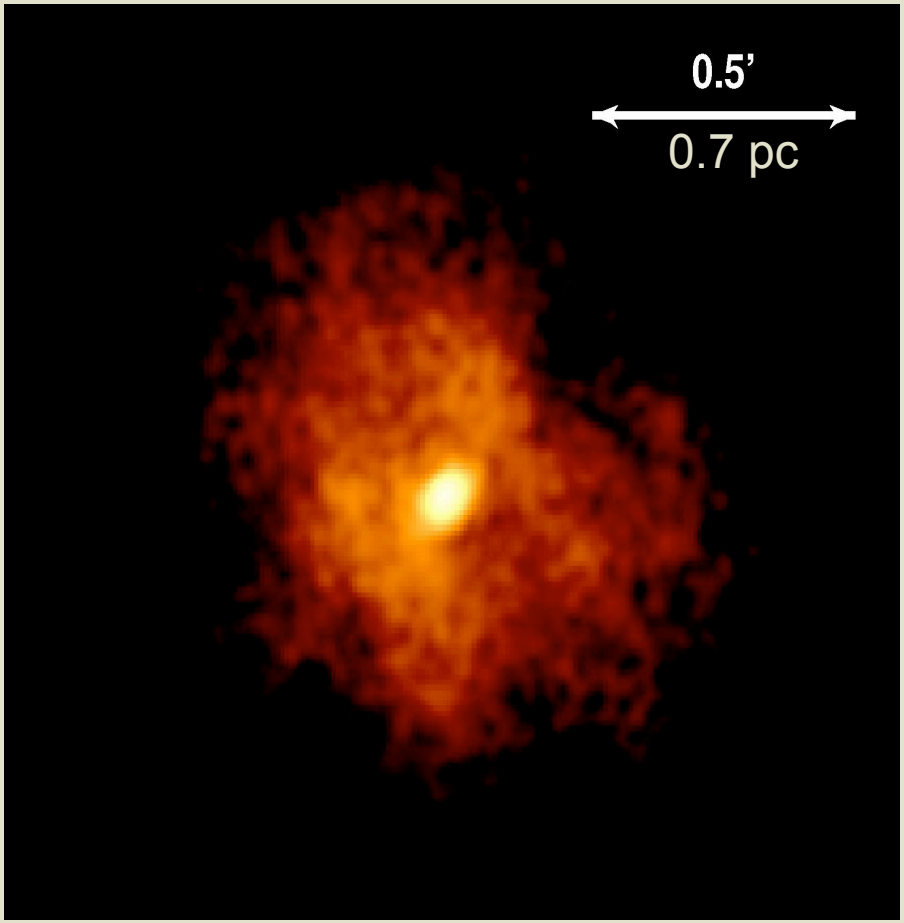
(Gaensler et al.
2002)

More examples of ~symmetric PWNe

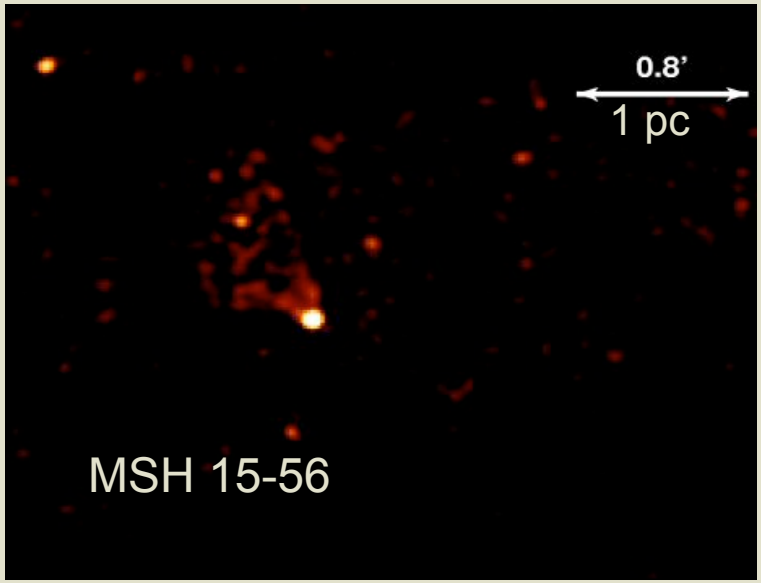
In **N157B** (LMC), PSR J0537-6909

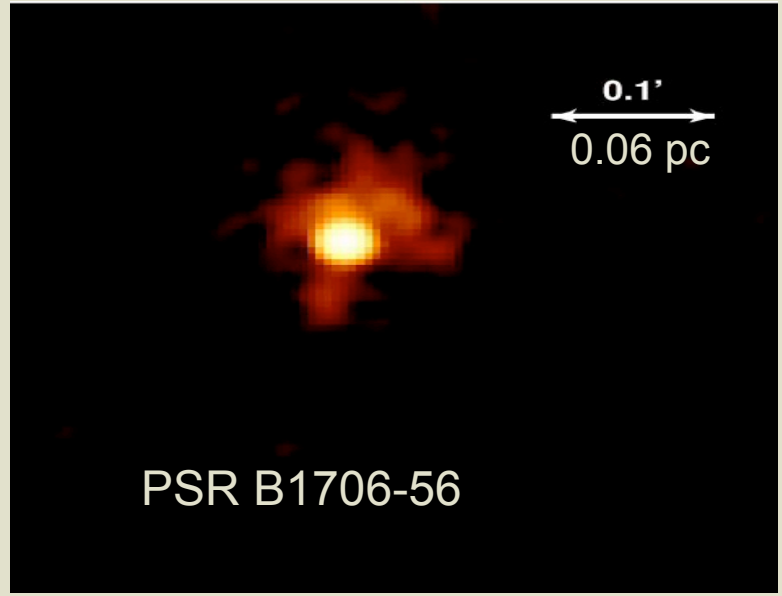


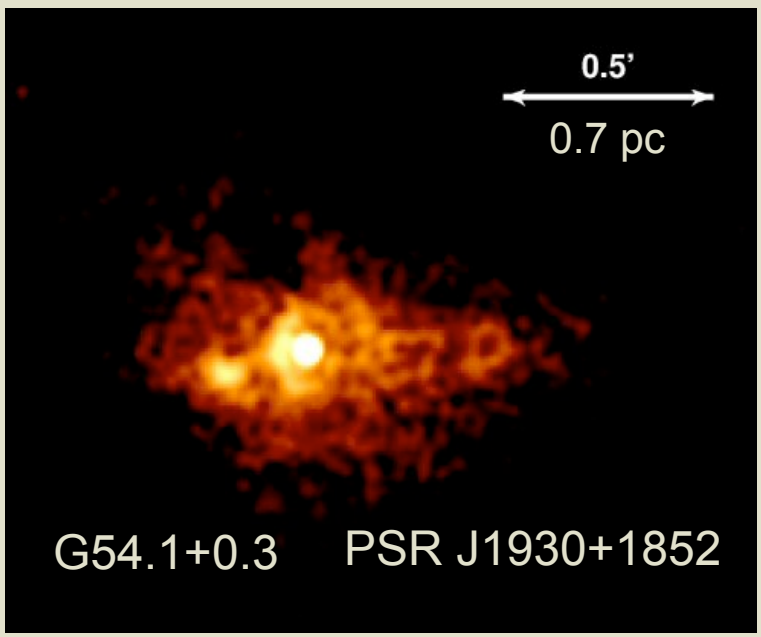
In **G21.5-0.9**, pulsar undetected

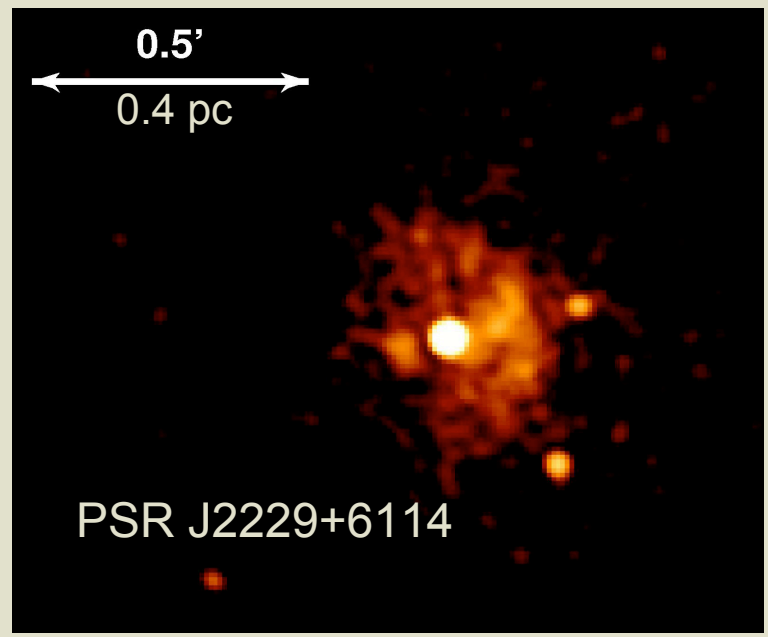


More examples…

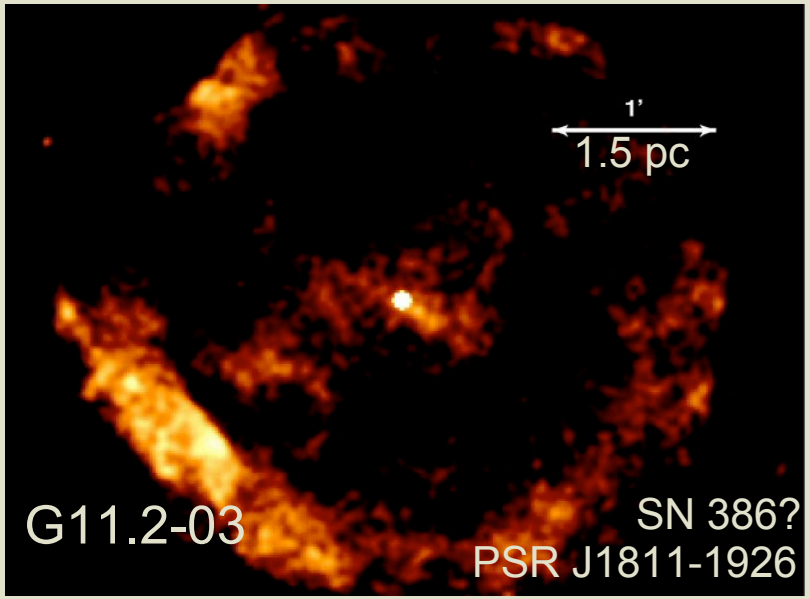


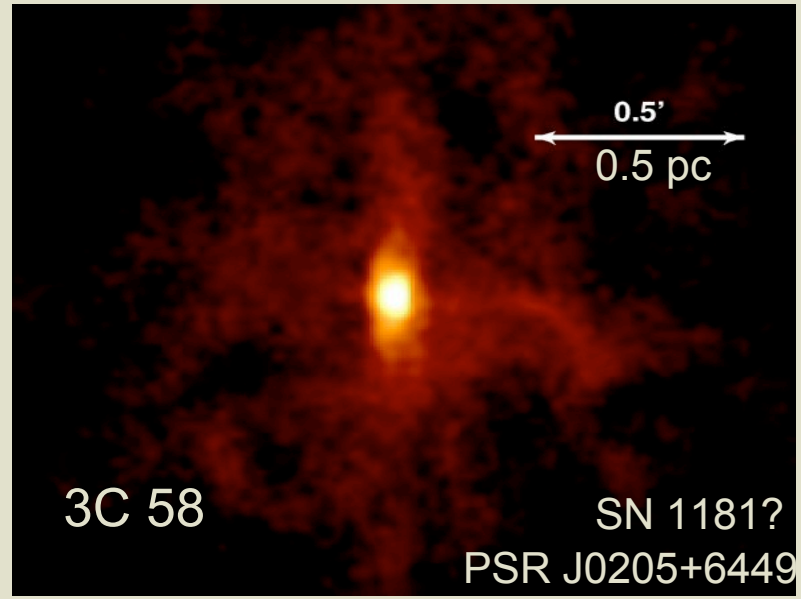


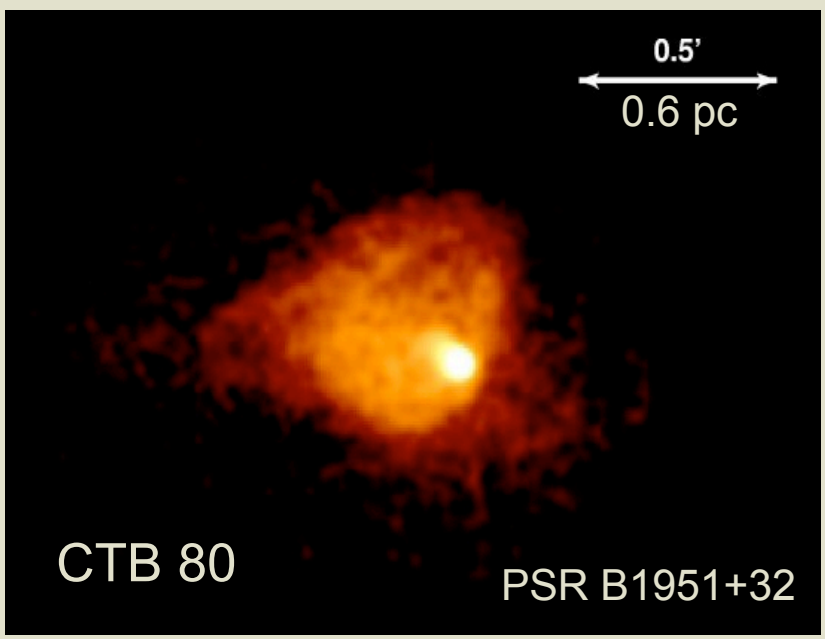


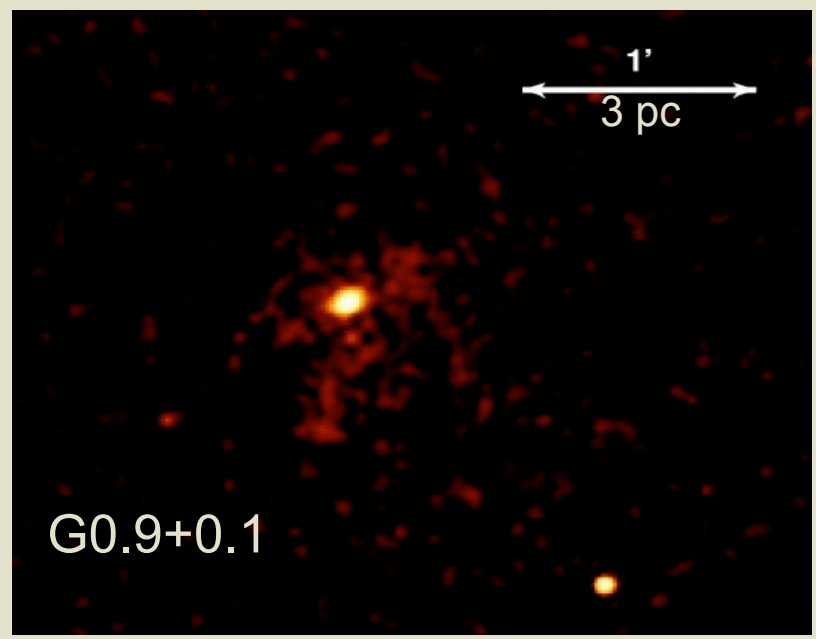


Not so clear symmetry..









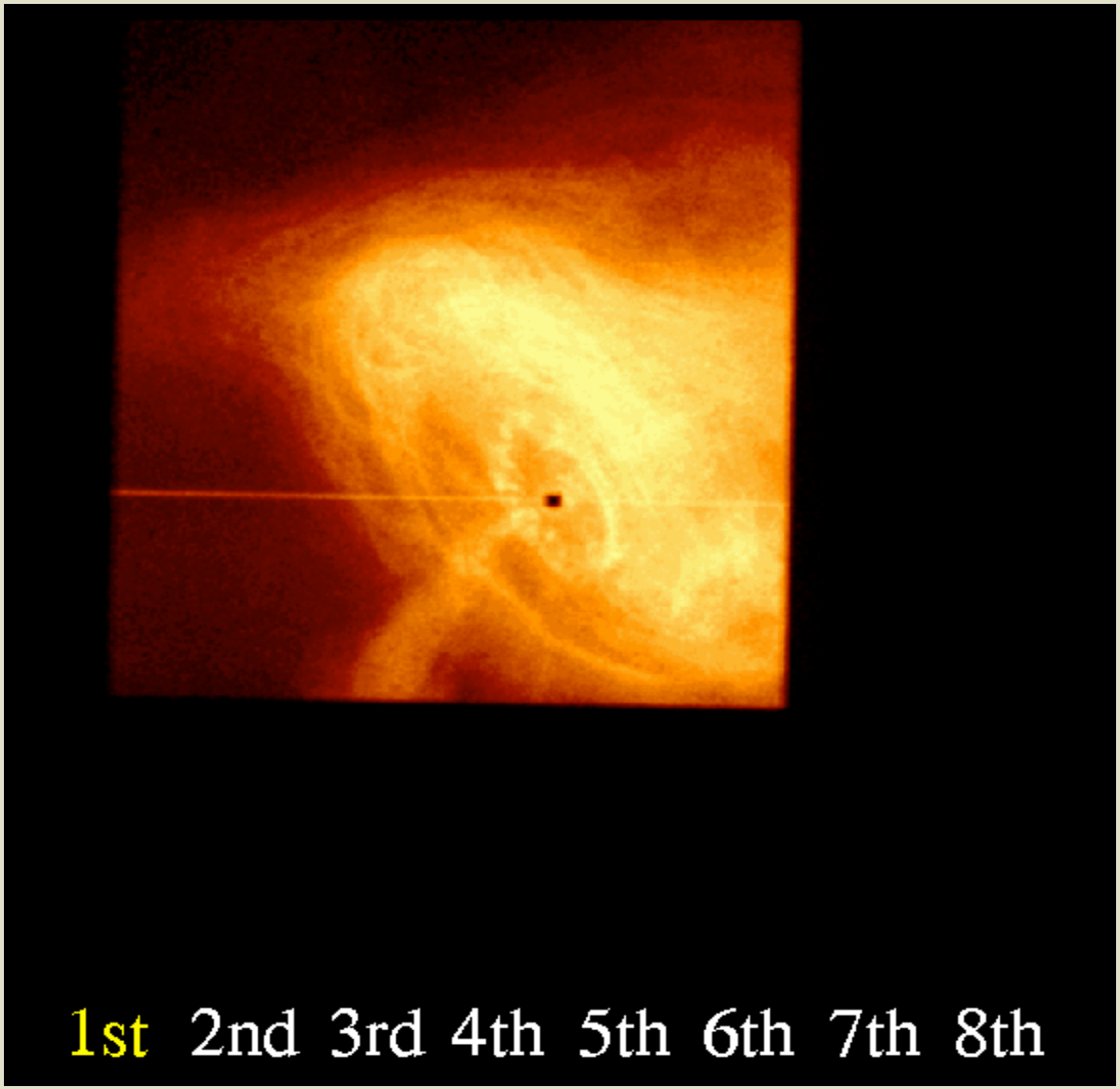
PWNe are dynamic objects

Crab: moving wisps, etc (Mori, Burrows, Hester 2002)

8 observations separated by ~3 weeks

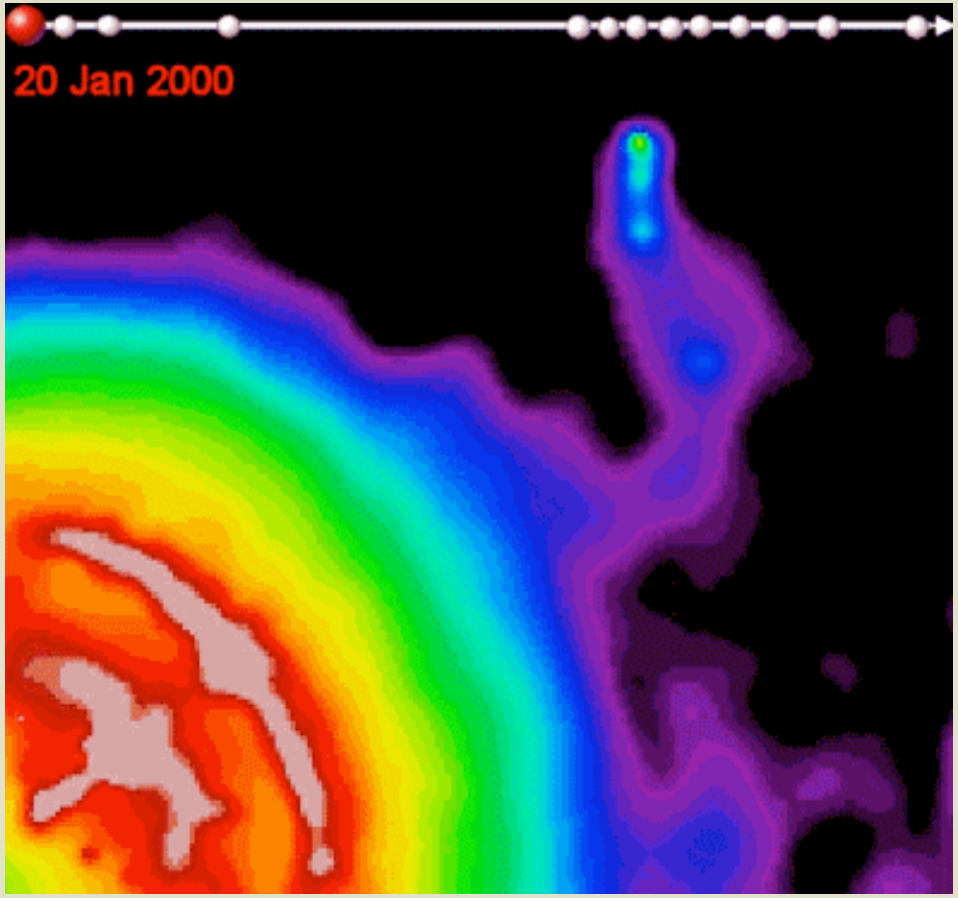
Speeds of outgoing wisps ~0.5c

Motions in torus ~0.15c



PWNe are dynamic objects

Vela: variable outer jet (Pavlov et al. 2003)



- Variability :

1. Sideways shifts/bends; ~ month
2. Outward moving blobs; v~0.6c
3. Blobs brightness varies; ~ week

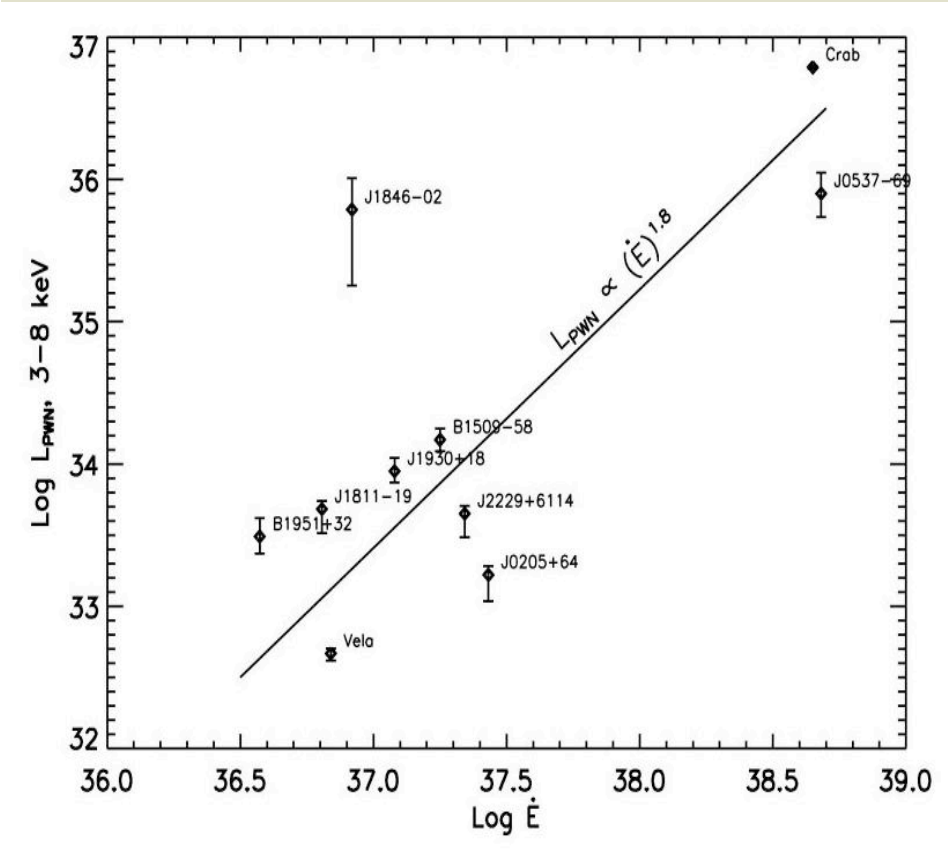
- Luminosty $L_X \sim 10^{30}$ erg/s

- Spectrum: power-law, photon index $\Gamma = 1.4 \pm 0.1$

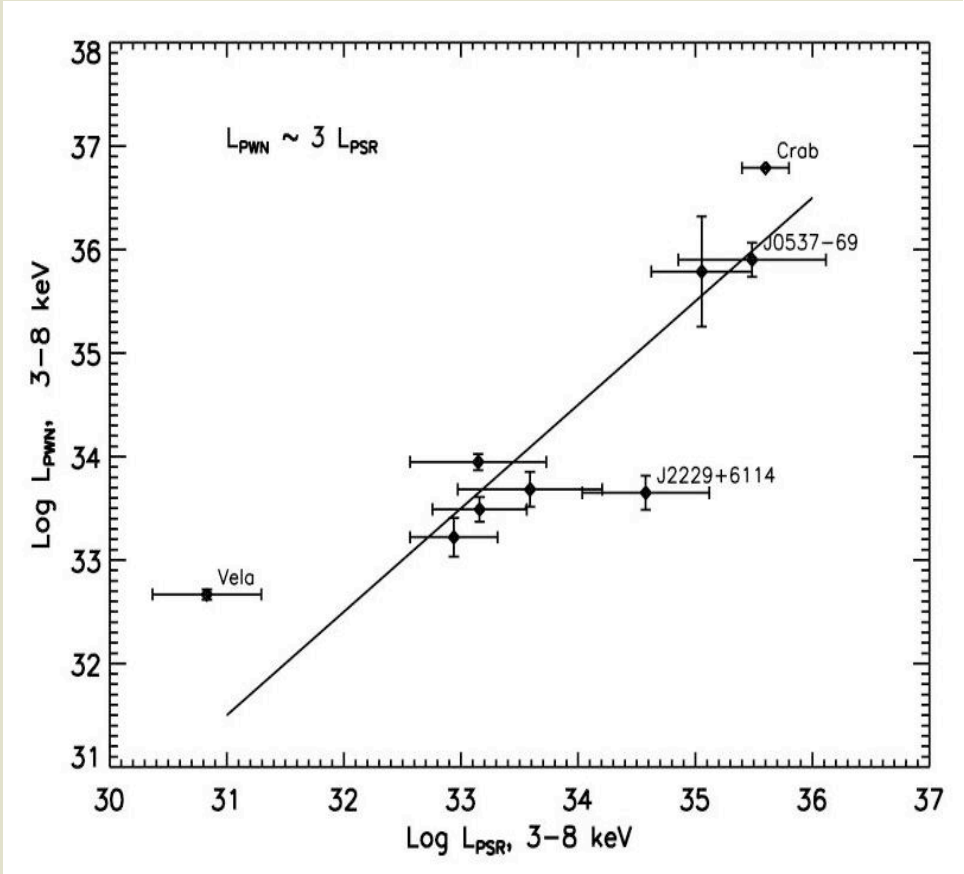
- Synchrotron emission in magnetic field B ~ 100 μG

X-ray luminosity of a PWN is a small fraction, 10^{-4} – 10^{-1}, of Edot

L_{PWN} correlated with Edot



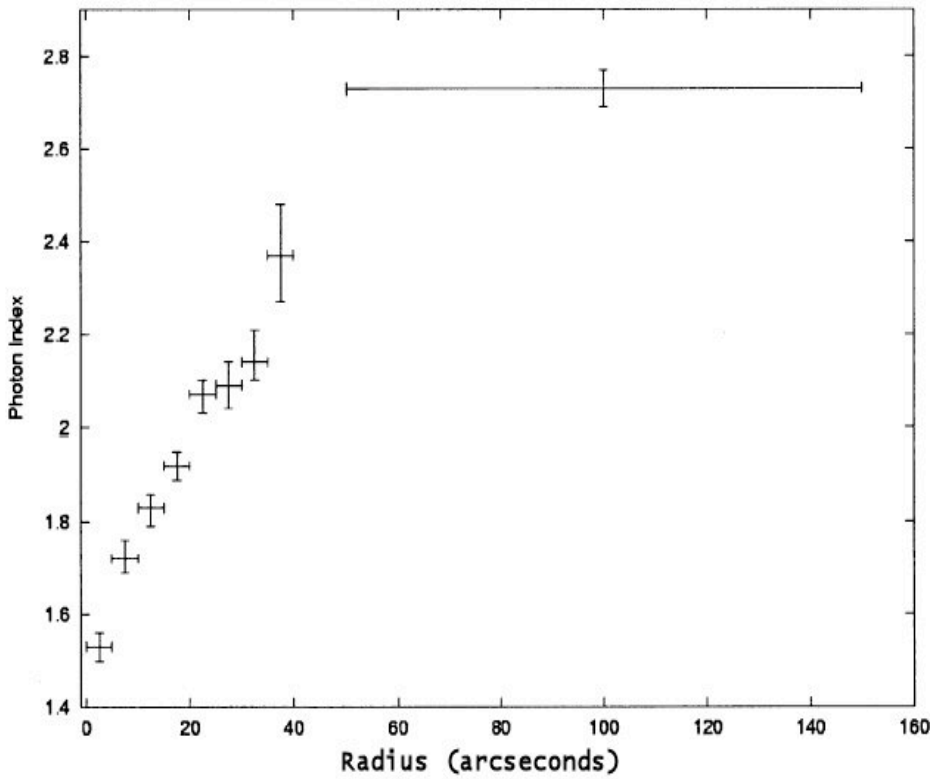
Even better correlated with L_{PSR}



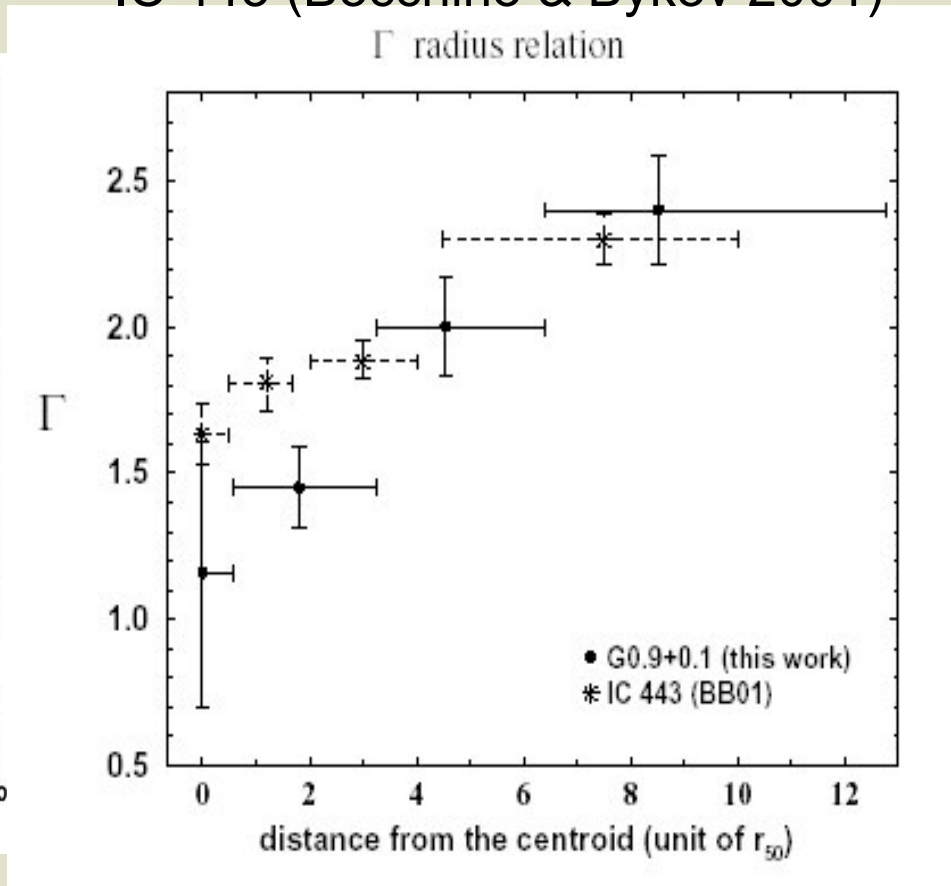
X-ray spectra: power laws with $\Gamma = 1 - 2.5$

Generally, spectra soften with increasing distance from PSR

G21.5-0.9 (Safi-Harb et all. 2001)



G0.9+0.1 (Porquet et al. 2003)
IC 443 (Bocchino & Bykov 2001)



Spectral slope correlates with morphology

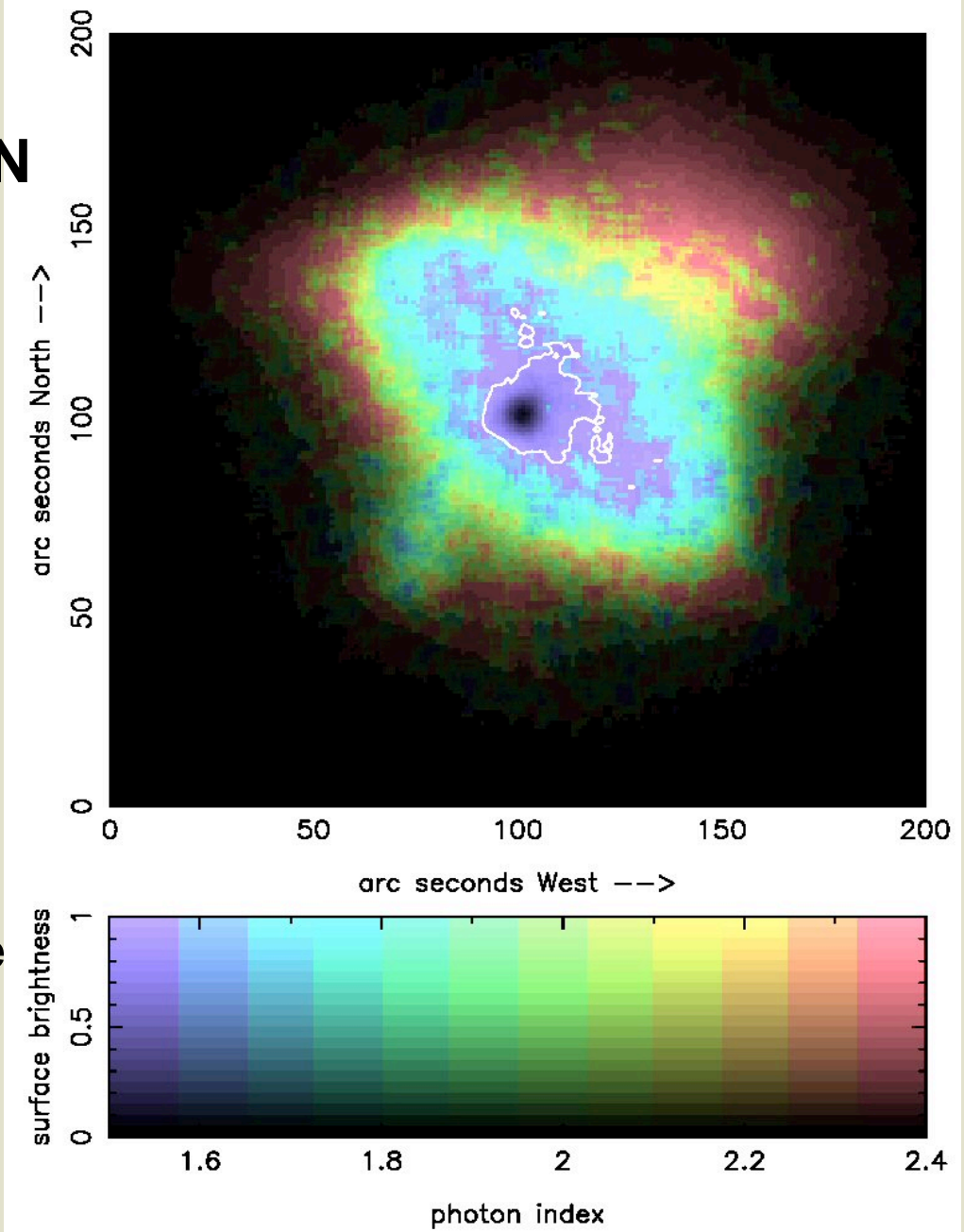
(not just a function of radius)

Spectral map of **Crab PWN** from XMM-Newton (Willingale et al. 2001)

Blue = hardest, Γ = 1.6;
red = softest, Γ = 2.4

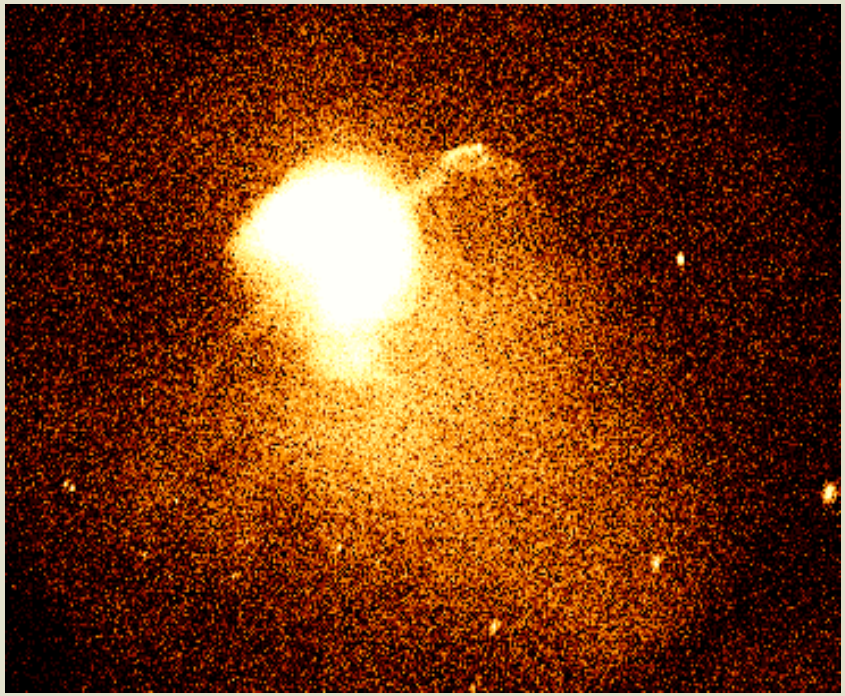
Spectrum generally softens towards the PWN periphery, but not isotropically

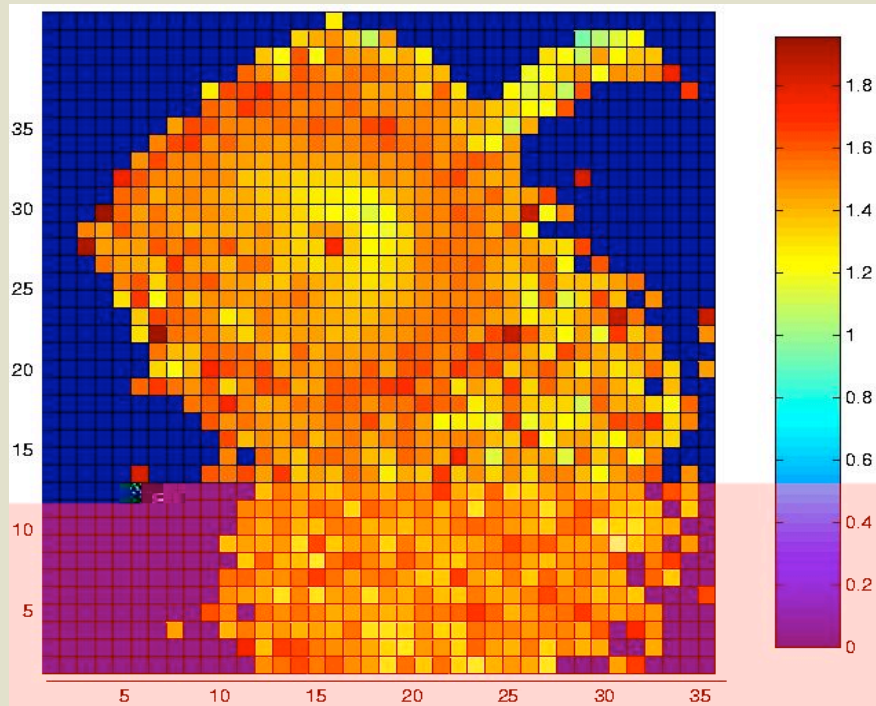
Fine structures (e.g., wisps) are not seen, perhaps because of low angular resolution



Chandra resolution → fine structure of spectral map

Spectral map of the **Vela PWN**:
red = soft, $\Gamma = 1.9$,
yellow = hard, $\Gamma = 1.2$





Outer jet and outer nebula are **harder** than inner PWN shell

Chandra observations have shown that PWNe have complicated morphology, often with axial symmetry (equatorial and polar outflows), associated with pulsar spin.

A model (Coroniti 1990): "striped wind" with toroidal magnetic field of alternating polarity, stripes separated by current sheets; predicts a "helical wind" along the spin axis; no model for collimated jets.

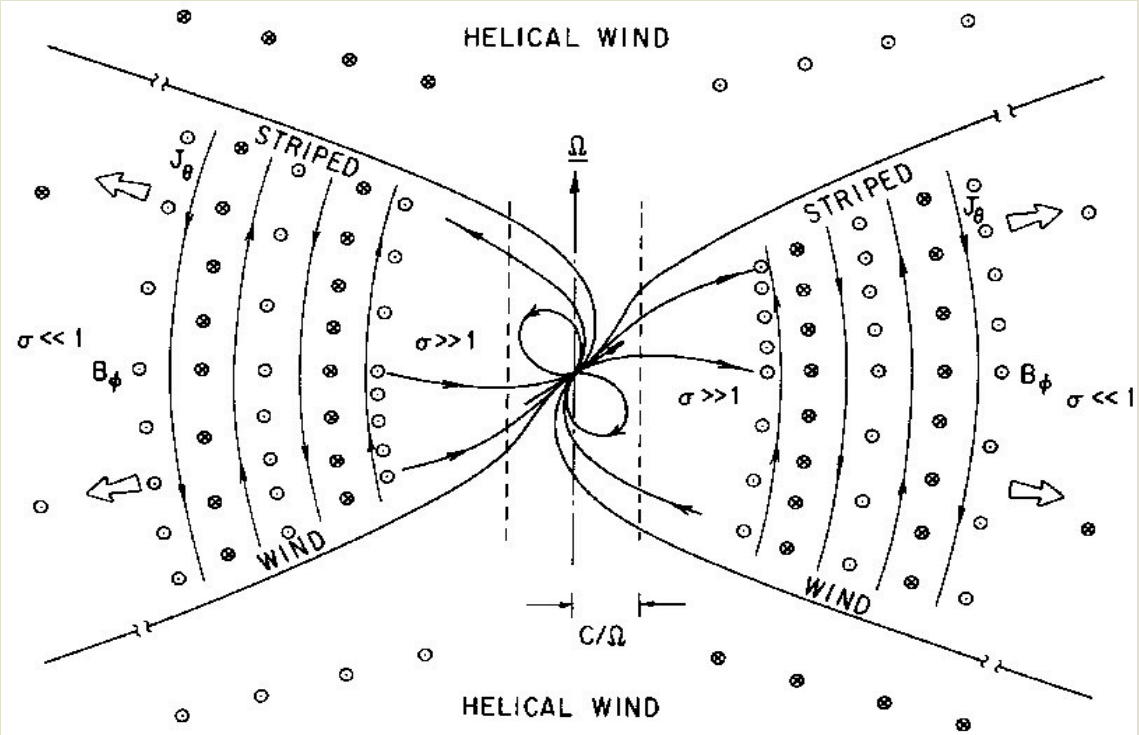


FIG. 1.—Sketch (not to scale) of a plausible magnetic topology for a relativistic MHD wind from an oblique rotator. Near the rotational equator, the toroidal magnetic field B_ϕ has an alternating polarity. These magnetic stripes are separated by thin current sheets (J_θ). Off the equator, the magnetic flux in the toward and away stripes is unequal if the dipole obliquity is not equal to $\pi/2$. Opposite flux regions of an initially high σ wind slowly annihilate, resulting in a low σ, thermally hot wind at large distances. Near the rotational poles, the toroidal magnetic field should be helically wound, because the flux originates in a single polar cap.

Some PWNe show very complicated structure, without a clear symmetry, perhaps due to various instabilities, nonuniformities of the ambient medium, etc.

Geometry of the magnetic field provides a clue for understanding the nature of these MHD flows.

Direct way to probe the magnetic field geometry:
Polarization measurements.

Polarization of synchrotron radiation:

Linear; direction of electric vector perpendicular to magnetic field. Degree of polarization:

$$q = \Gamma\,(\Gamma+2/3)^{-1}$$

$$\Gamma = 1 - 2.5 \quad \rightarrow \quad q = 60\% - 80\%$$

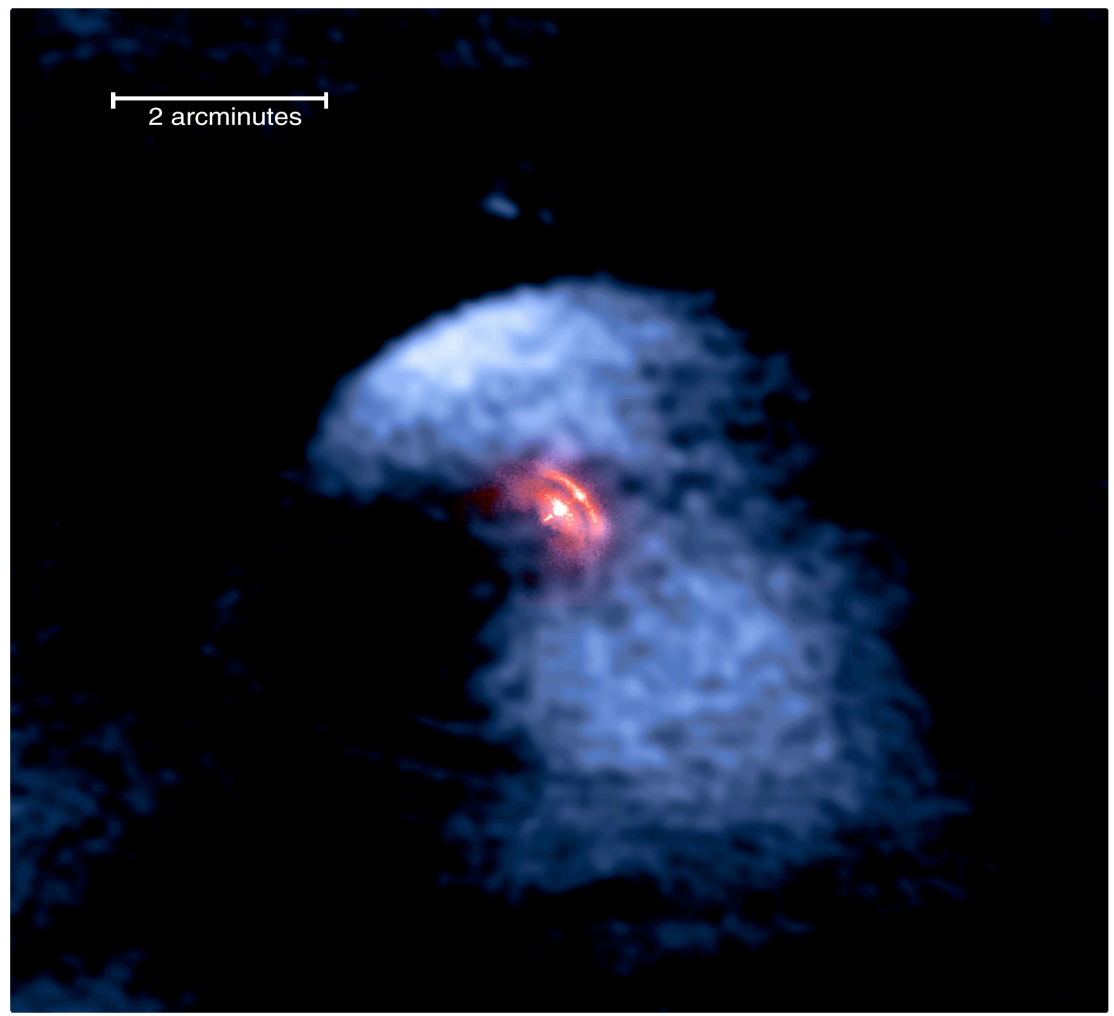
Polarization can be easily measured in radio, BUT:

- requires correction for (nonuniform) Faraday rotation
- radio is bright at larger distances from the pulsar
- strong contamination from the much brighter pulsar

Vela PWN:

pink: X-rays,
blue: radio (Dodson et al 2003)

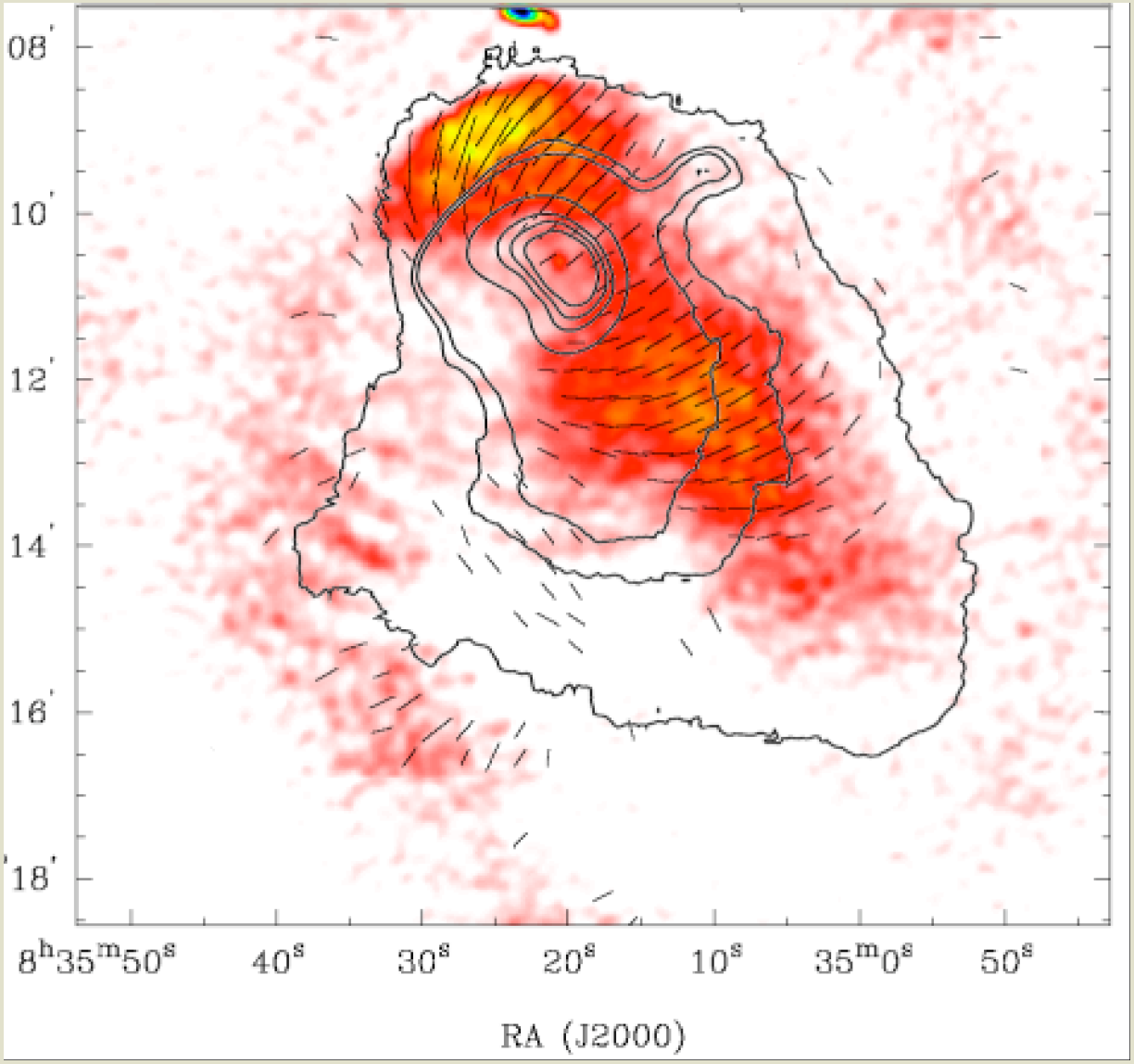
Radio is brighter at larger distances due to synchrotron + adiabatic cooling of the anisotropic outflow



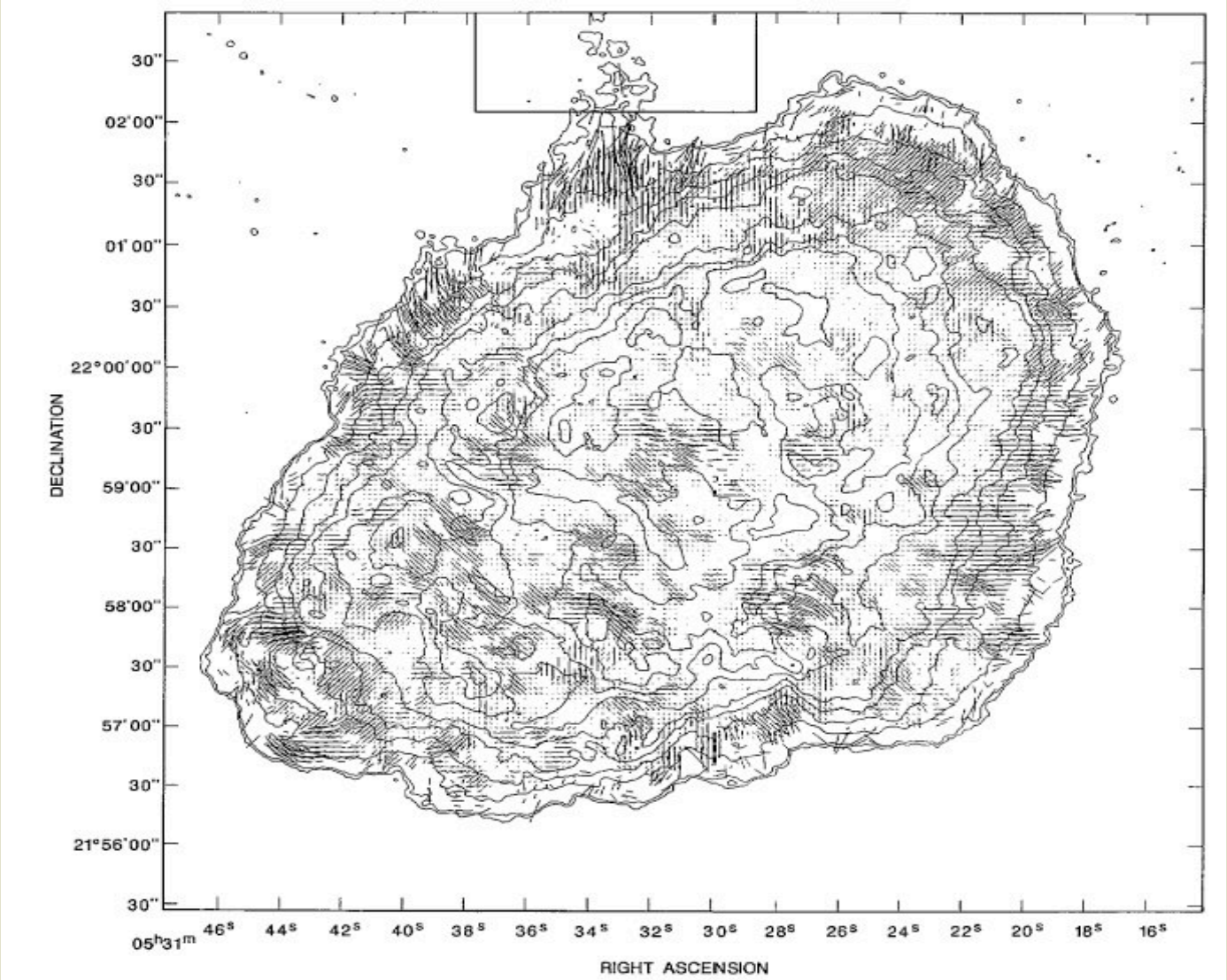
Vela PWN: X-rays vs. radio

X-ray contours follow the shape of the radio PWN:

Black dashes mark direction of polarization (i.e. perpendicular to magnetic field direction)



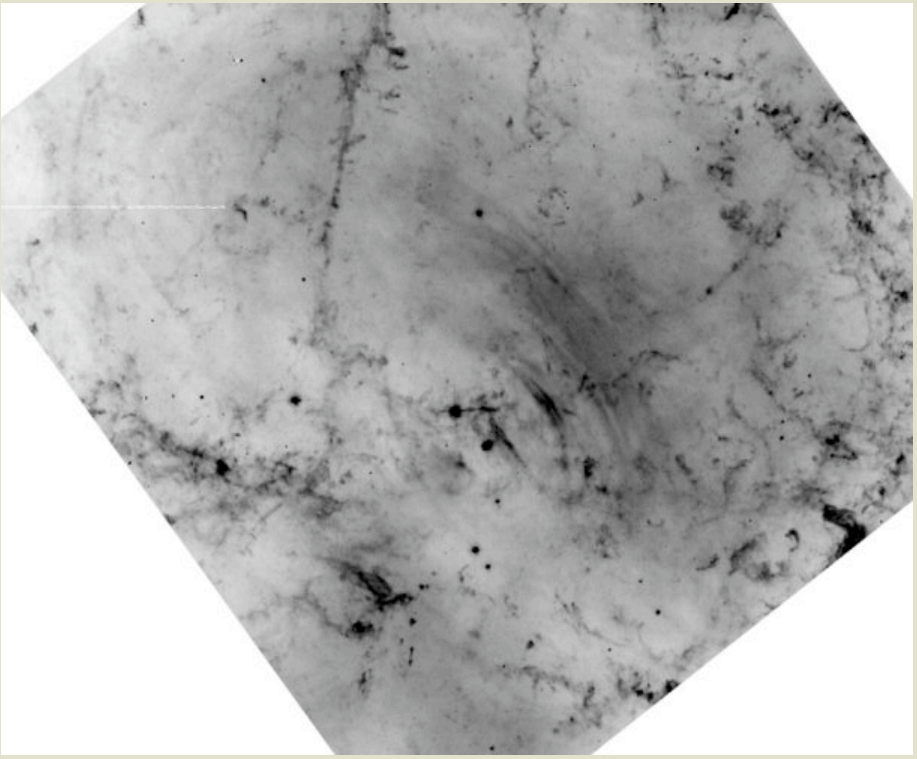
Crab: Radio


DECLINATION
30"
02'00"
30"
01'00"
30"
22°00'00"
30"
59'00"
30"
58'00"
30"
57'00"
30"
21°56'00"
30"
05h31m 46s 44s 42s 40s 38s 36s 34s 32s 30s 28s 26s 24s 22s 20s 18s 16s
RIGHT ASCENSION

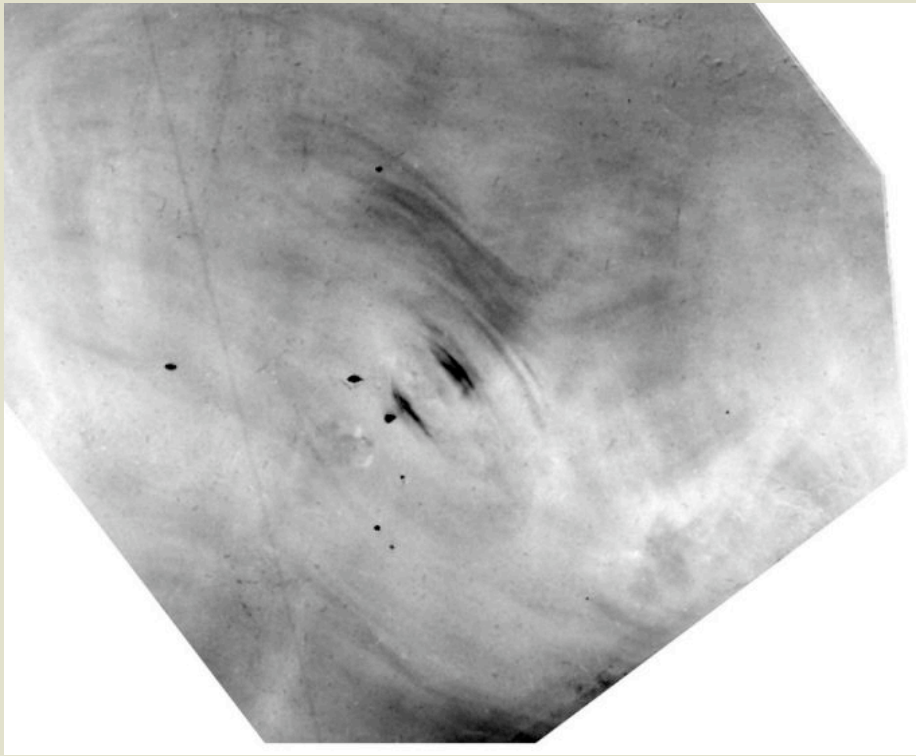
PWN polarization can be observed in optical but for very few objects.

HST/ACS observations of **Crab** (Hester et al 2004)

Total intensity

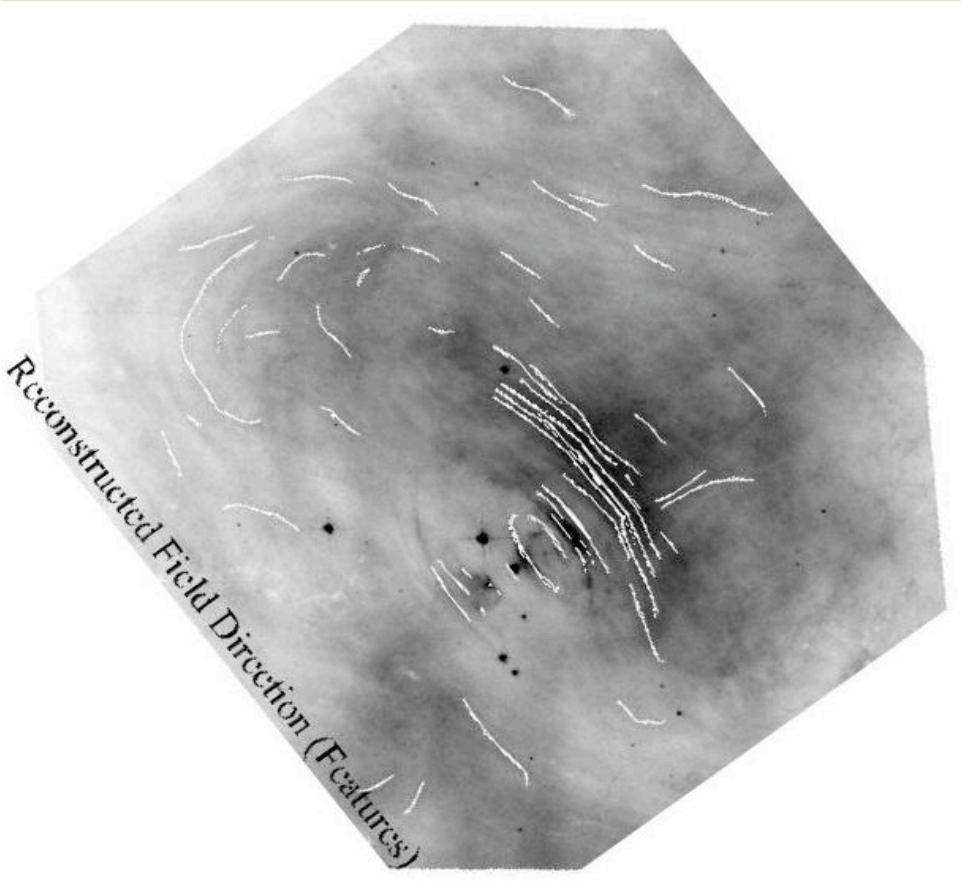


Polarized intensity

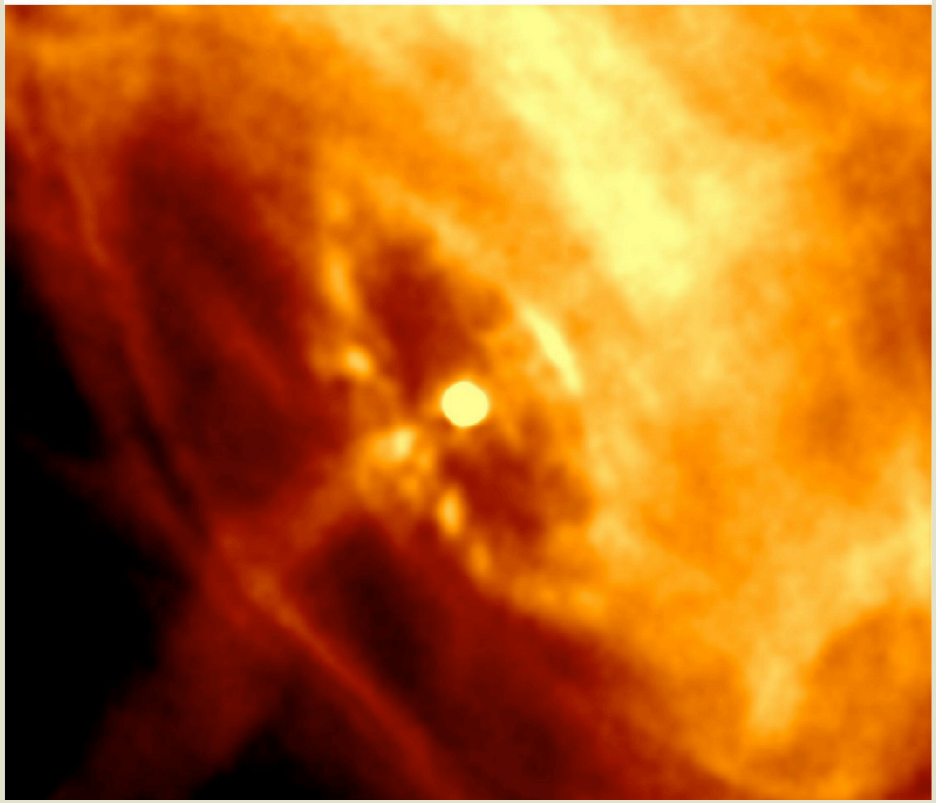


q up to 50%,
strong depolarization at SW

Crab: Polarized intensity + directions of magnetic field (white lines)



X-ray intensity



Magnetic field is indeed mostly toroidal

Polarization in X-rays

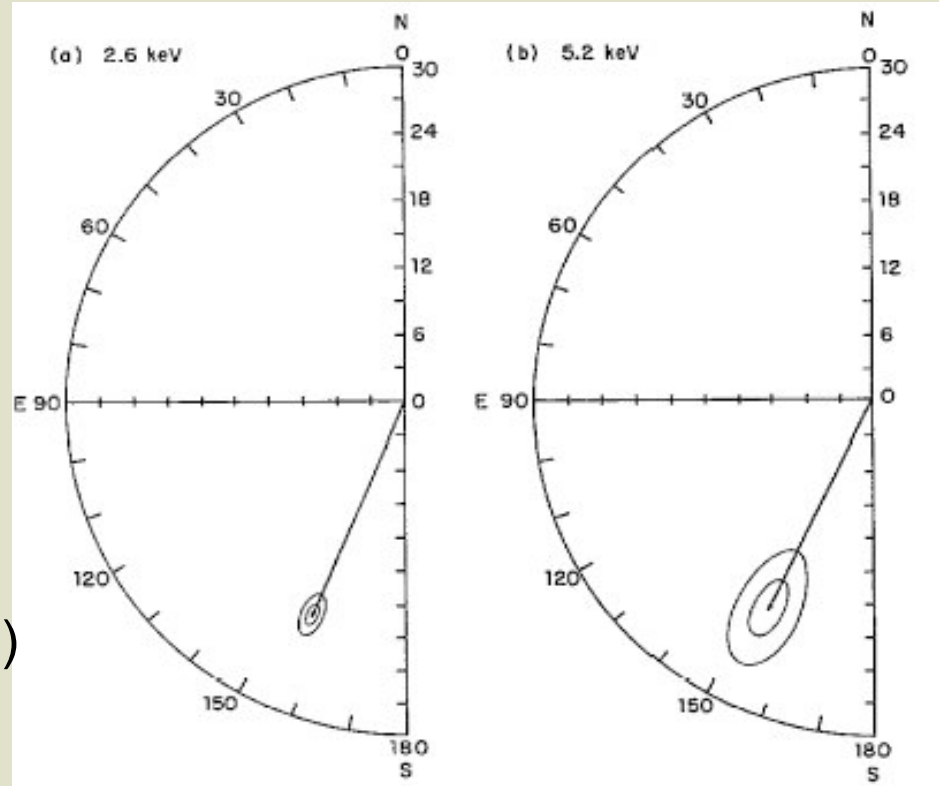
Detected from Crab only; the latest observations with ***OSO 8*** in **1976-77**, 71 hours total @ 2.6 and 5.2 keV (Weisskopf et al 1976,1978).

Net result:

q = 19.2 +/- 1.0%,
P.A. = 156.4 +/- 1.4 deg @ 2.6 keV

q = 19.5 +/- 1.8%,
P.A. = 152.6 +/- 4.0 deg @ 5.2 keV

Generally consistent with radio/optical, given poor angular resolution (~0.5 deg) and nonuniformity of the magnetic field



- X-ray polarization observations directly probe topology of magnetic field and are helpful in understanding PWN physics
- X-rays are more suitable than radio because Faraday rotation/depolarization is negligible
- X-rays are more suitable than optical because PWNe are relatively bright in X-rays (more PWNe can be studied)
- Energy resolution is not required, time resolution useful to separate pulsar's contribution

BUT

- Observations with low angular resolution provide only average direction of magnetic field, not very useful for understanding fine structures

We need another Chandra, with a polarimeter