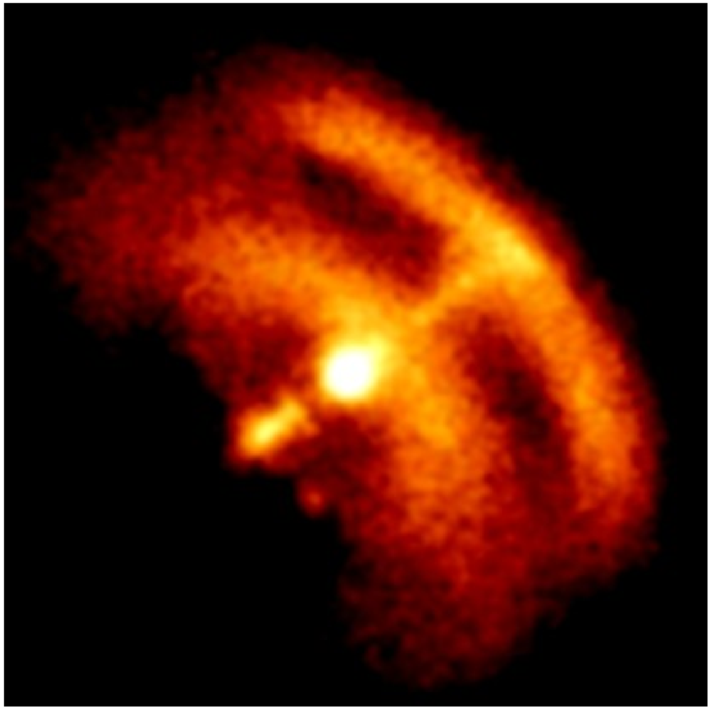
Chandra view of the dynamic Vela PWN



George Pavlov (Penn State University)
Oleg Kargaltsev (University of Florida)

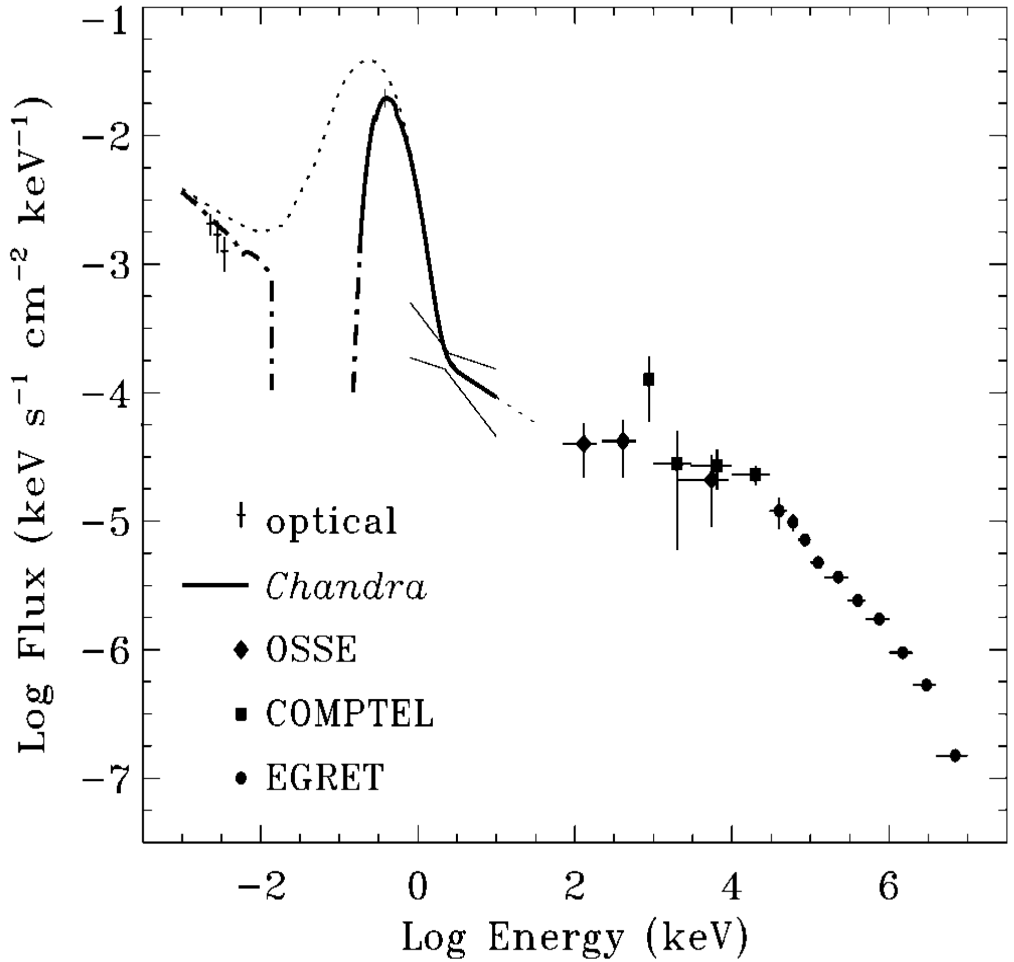
Vela pulsar (PSR B0833-45) in the Vela SNR

- P=89.3 ms
- $\dot{E}=7\times10^{36}$ erg/s
- $B=3.4\times10^{12}$ G
- τ =11 kyrs

D = 300 pc

UV and soft X-ray emission is thermal (NS surface with **kT ~ 60 - 120 eV**)

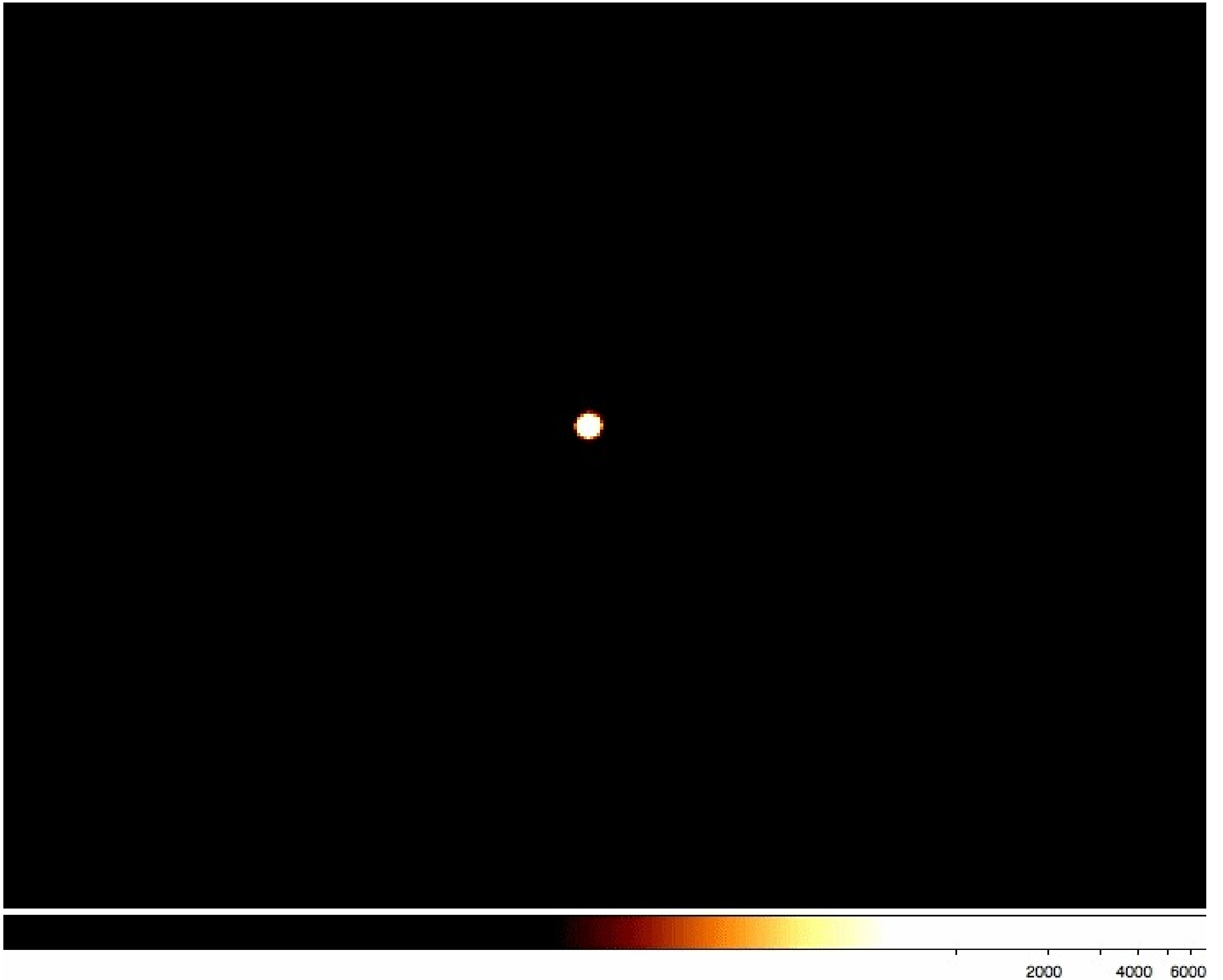
Optical, hard X-rays and γ-rays from the magnetosphere; power-law spectrum with varying photon index Γ.



In the Chandra energy band: $\Gamma \approx$ **1.5**; nonthermal luminosity

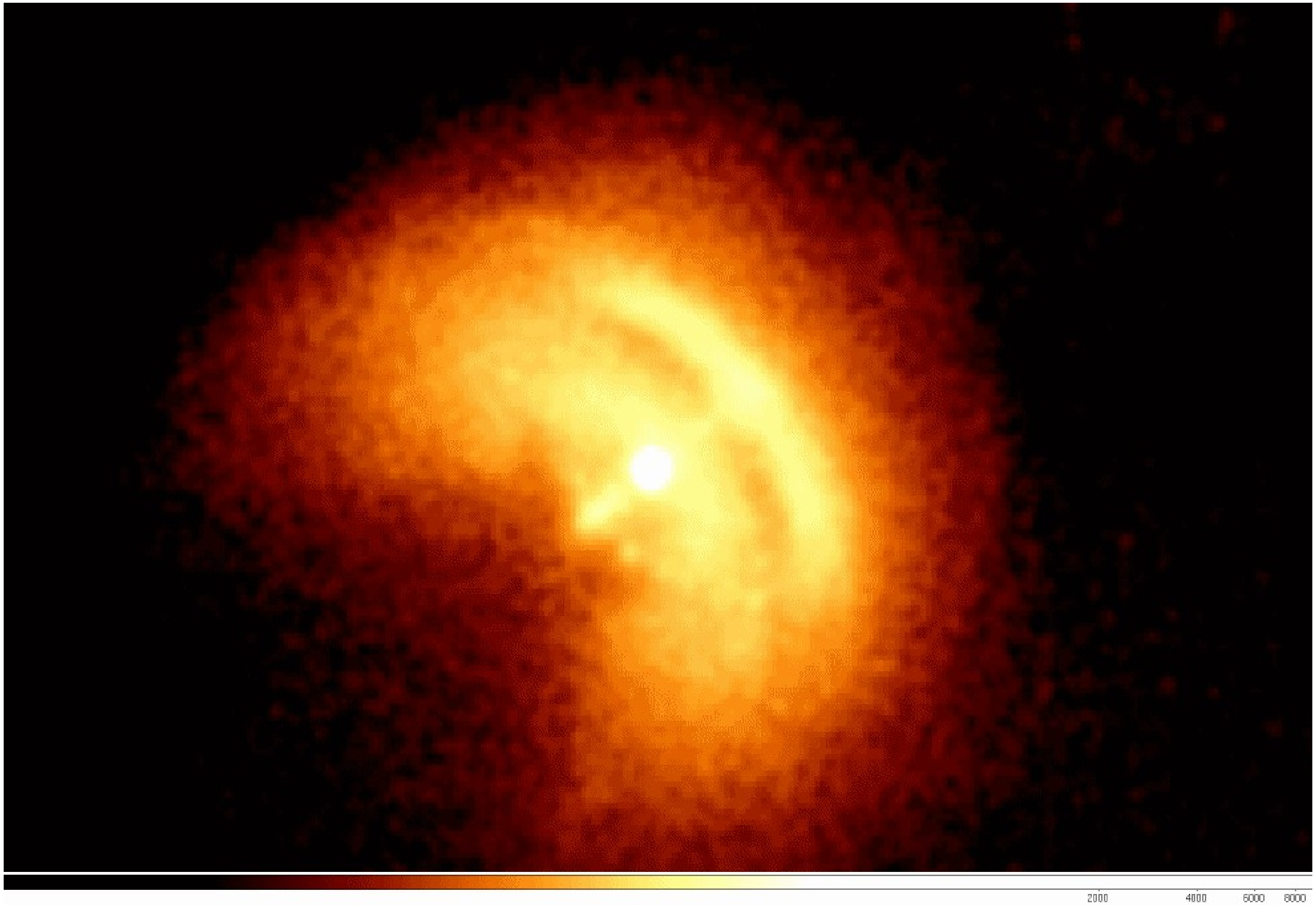
$L_{0.2\text{-}8\,keV}$ ~ 1.5×10^{31} erg/s ~ $2\times10^{-6}\,\dot{E}$ -- very low X-ray efficiency

First Chandra observation (HRC-I, 50 ks, 20 Jan 2000, PI D. Helfand) showed a stunning picture (two arcs, inner “jets” along the proper motion, a faint “hook” ahead of the compact PWN, asymmetric diffuse emission, etc)



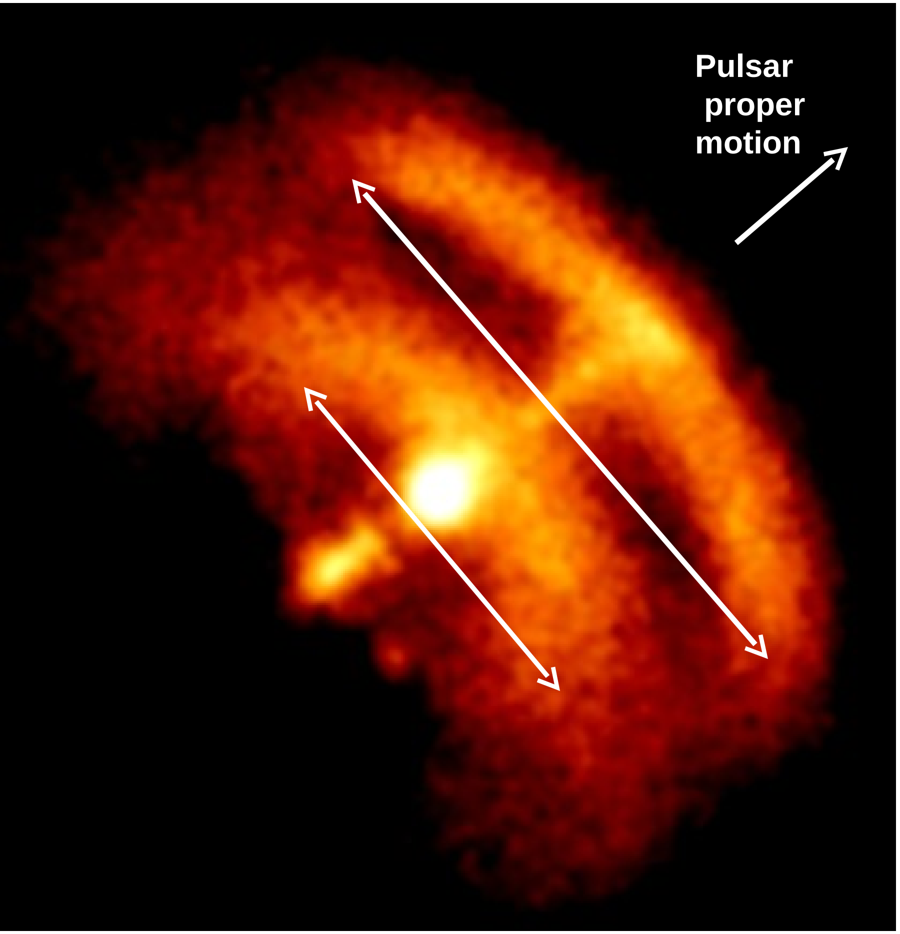
Varying the image size to better see the faint diffuse emission

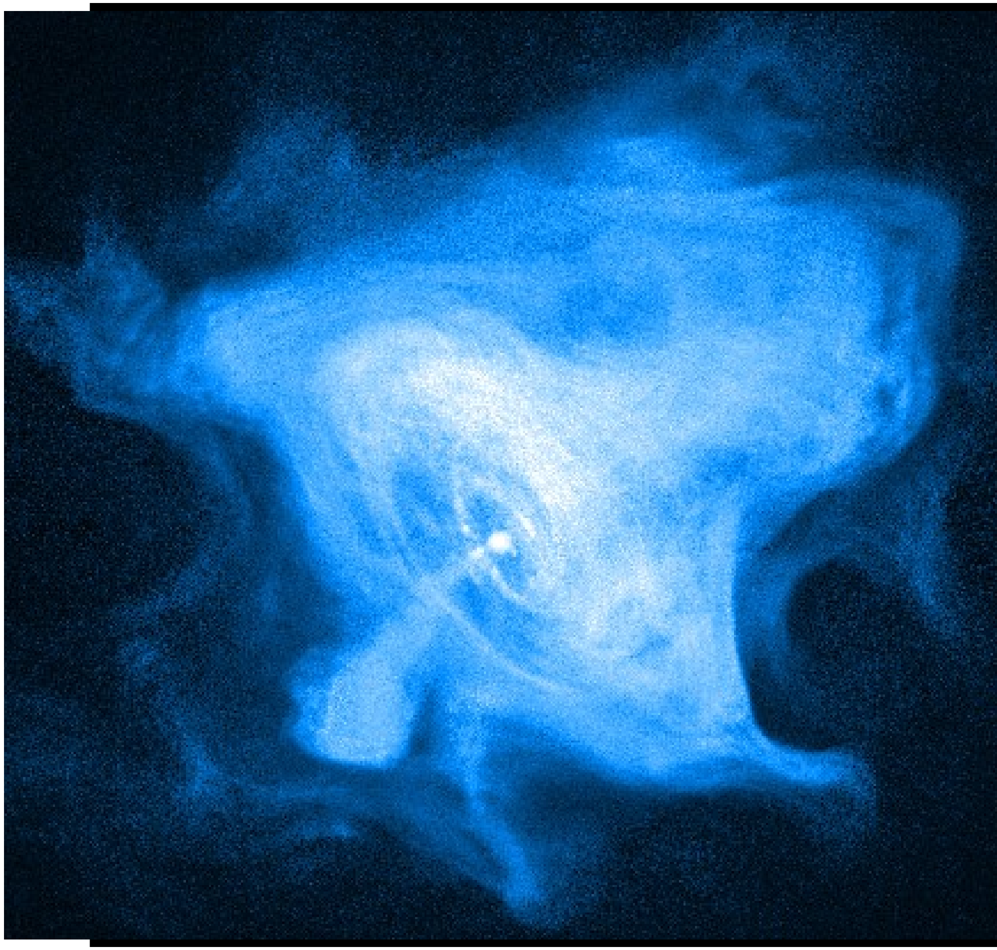
Three HRC-I observations (Jan 2000, Feb 2000, Jan 2002), 150 ks total



ACIS observations of 2001-2002: Bright Inner PWN

8 × 20 ks = 160 ks; 1–8 keV

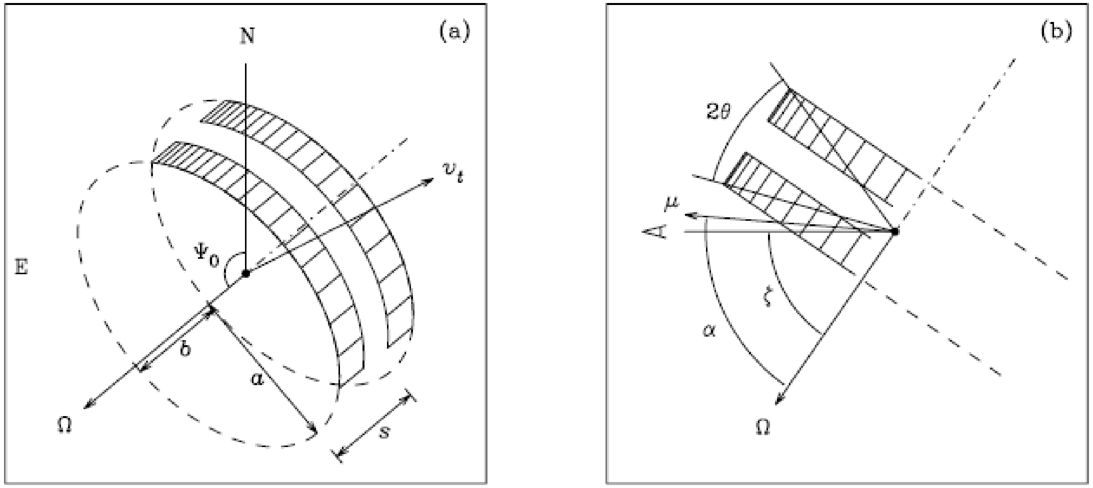




Inner arc is (Doppler-boosted?) part of a ring, perhaps a termination shock, but the pulsar is not in the ring's plane. If the **Outer Arc** is part of a ring, the ring's size is a factor of 1.4 greater; it, however, may be an umbrella-like surface, not a ring. The nature of the **"jets"** is even less clear.

The overall topology resembles that of the Crab but there are differences (because of different angles between the magnetic and spin axes?)

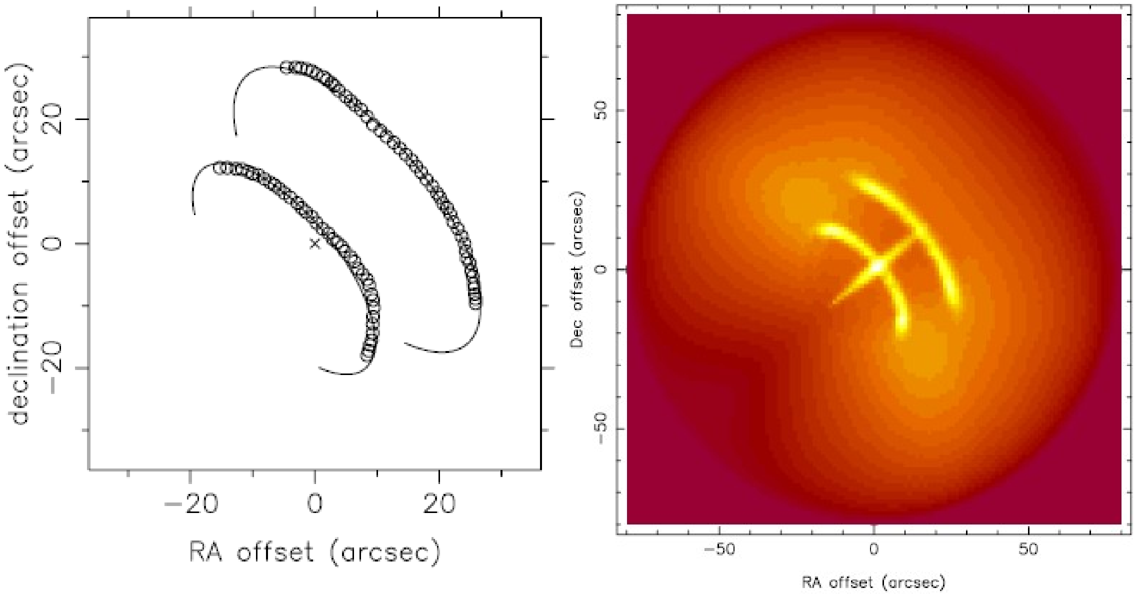
The very different interpretations of the PWN morphology



Helfand et al 2001

The **arcs** highlight a shock in an equatorial outflow (23 deg opening angle; no emission in the equatorial plane because B=0 there).

The **jets** might be polar outflows along the spin axis, which coincides with the direction of pulsar motion.

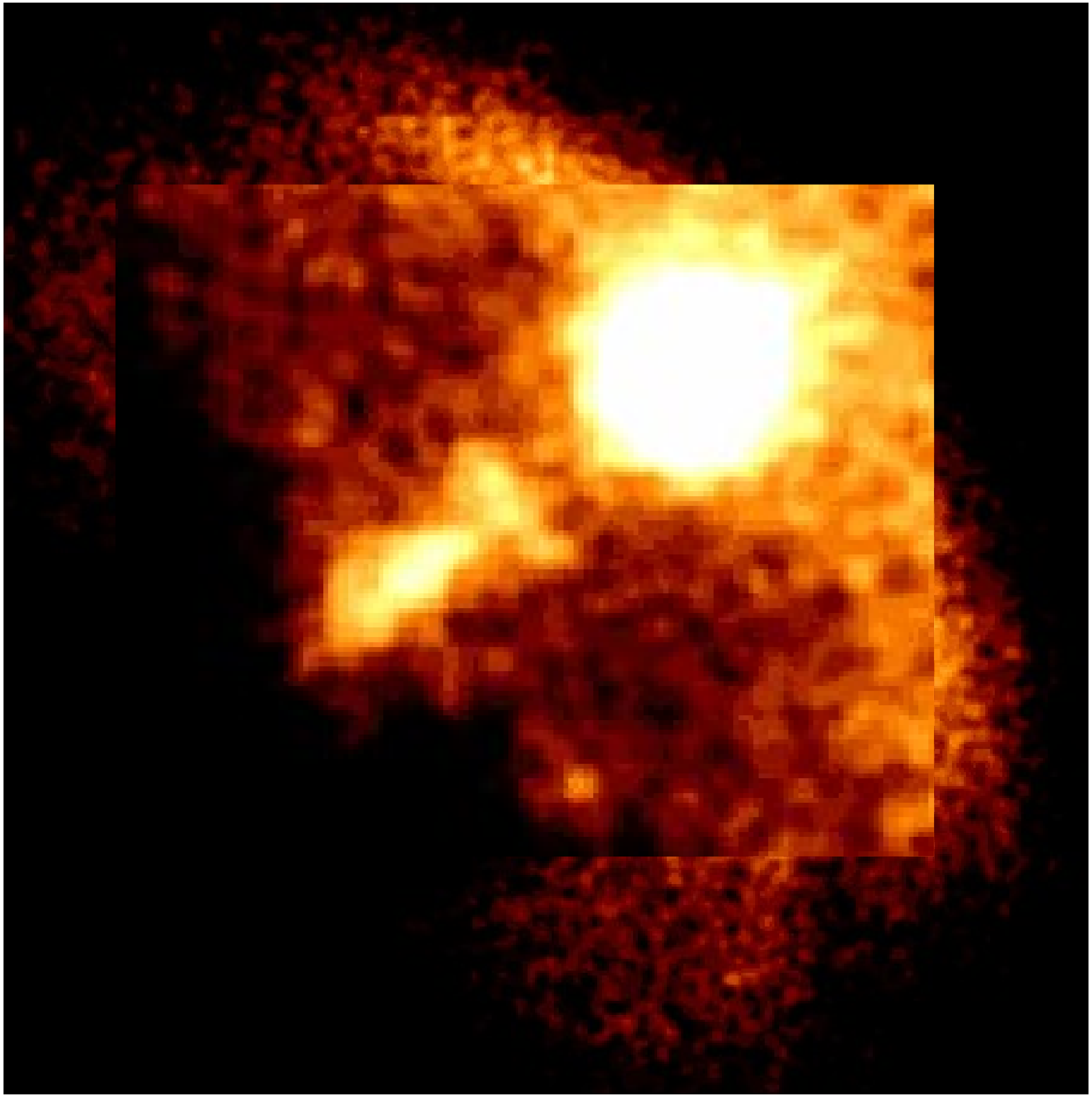


Radhakrishnan & Deshpande 2001

The **arcs** trace rotating particle beams from the two magnetic poles (possibly along the magnetic axes) at the shock front.

The “**jets**” are projections of the cones formed by the rotating beams, not real physical jets.

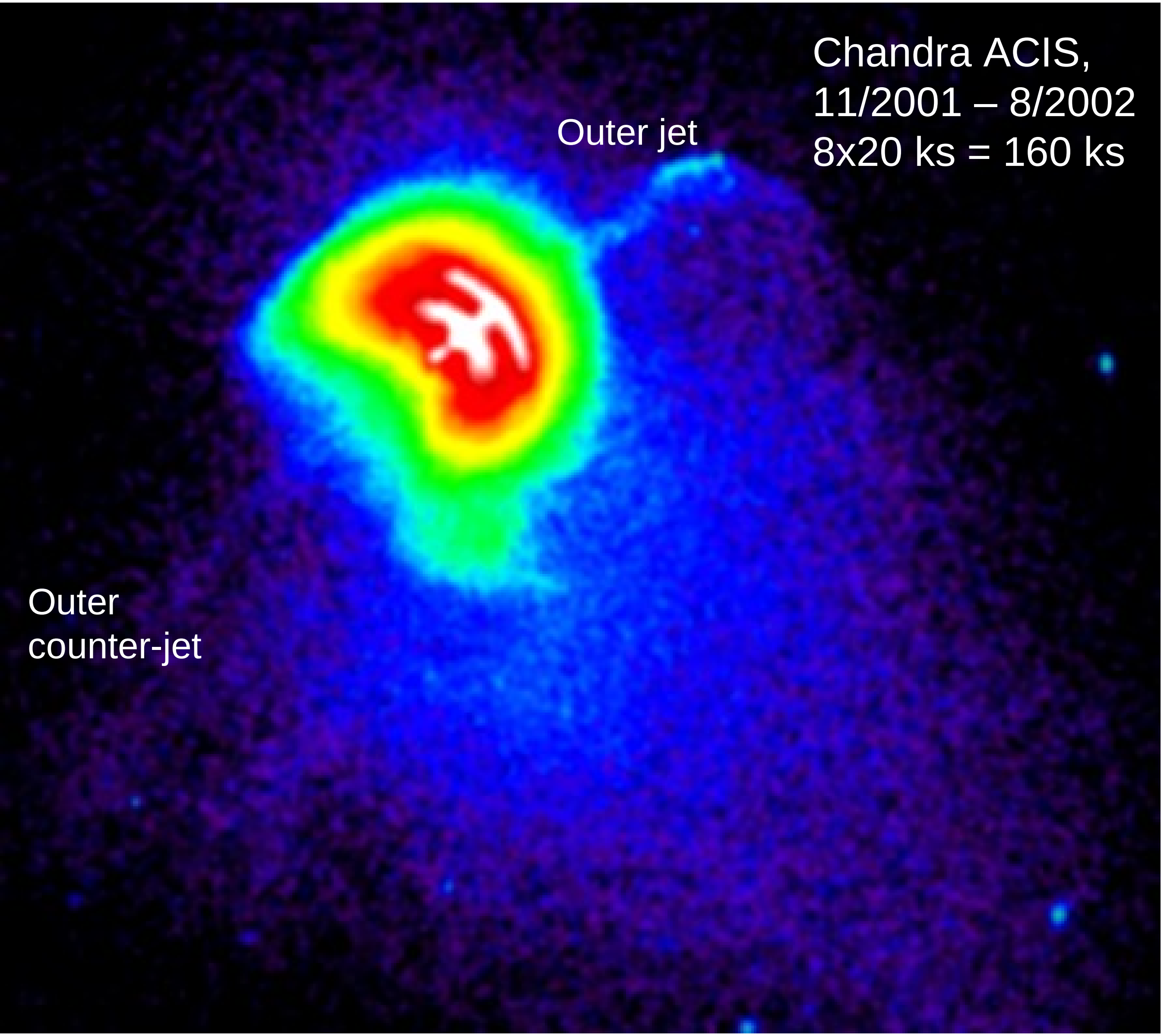
“Bar”: a shock in a polar outflow?



In this interpretation at least the SE jet is the physical jet, not just a projection

ACIS observations of 2001-2002: Large-scale structure

6’ × 5.5’ = 0.52 pc × 0.48 pc @ d=300 pc



Ram pressure due to PSR motion affects the shape of the compact PWN component

Outer counter-jet (or **tail?)** is seen, even fainter than the **outer jet**.

Large-scale diffuse emission SW of the compact PWN – blown off by an SNR “wind”?

Total luminosity

$\mathbf{L_{0.2\text{-}8\,keV} \sim 8 \times 10^{32}}$ **erg/s**

$\mathbf{\sim 10^{-4}\,\dot{E}}$

-- low X-ray efficiency

- Bright enough to provide high-S/N images and spectra
- Also very dynamical!

The Dynamic Outer Jet of the Vela pulsar

Length ~100 arcsec (4×10^{17} cm @ 300 pc) ; Luminosity 7×10^{30} erg/s (1% L_{PWN})

- Variability :

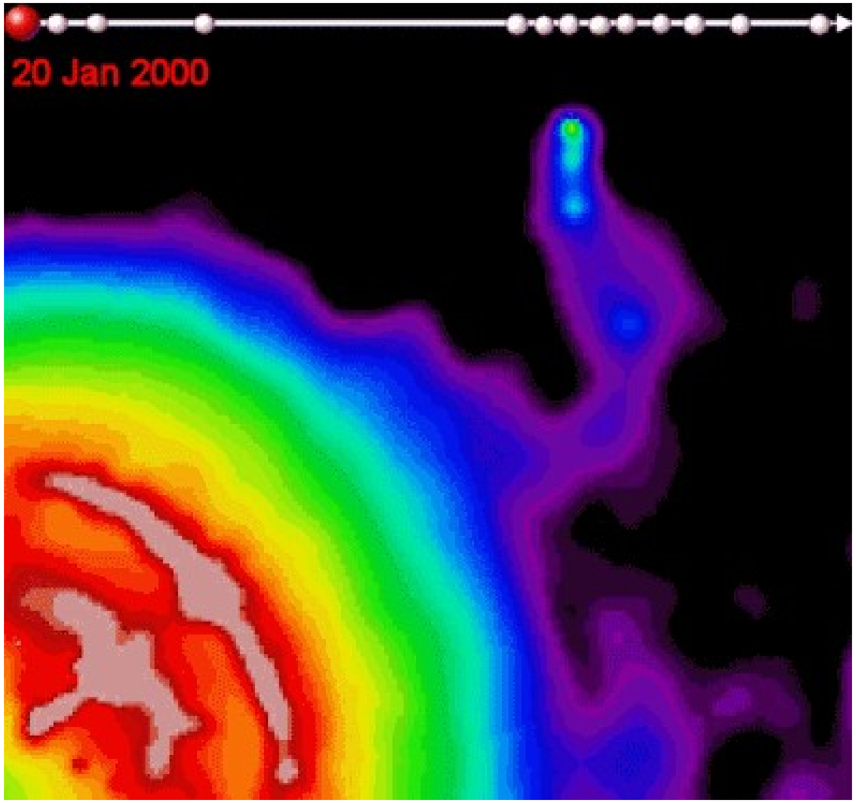
1. Sideways shifts/bends; ~ 1 month
2. Outward moving blobs; v~0.6c
3. Blobs brightness varies; ~ 1 week

- Orientation:

  blob speeds + outer jet/counter-jet brightness ratio => jet approaches observer at 30-60 deg angle;
  (*assuming equal intrinsic brightnesses for the jet/counter-jet !*)

- Spectrum: power-law, photon index $\Gamma=1.4\pm0.1$

- Synchrotron emission in magnetic field B ~ 100 μG



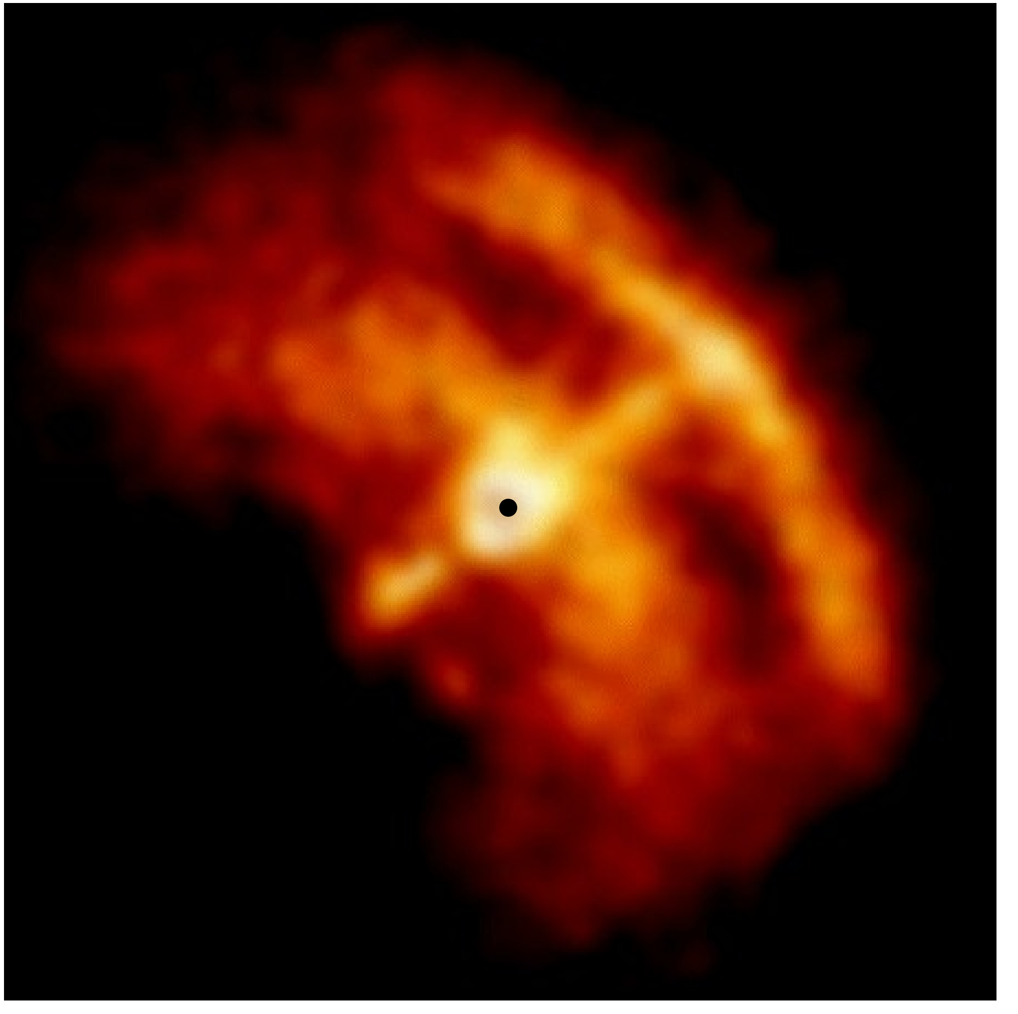
Vela Jet movie made of 13 Chandra observations (Pavlov et al. 2003)

Inner PWN: variability

Most variable features: bright spot, jets, outer arc;

Shape and brightness change on timescale of ~1 week;

No features similar to wisps in the Crab PWN are observed.

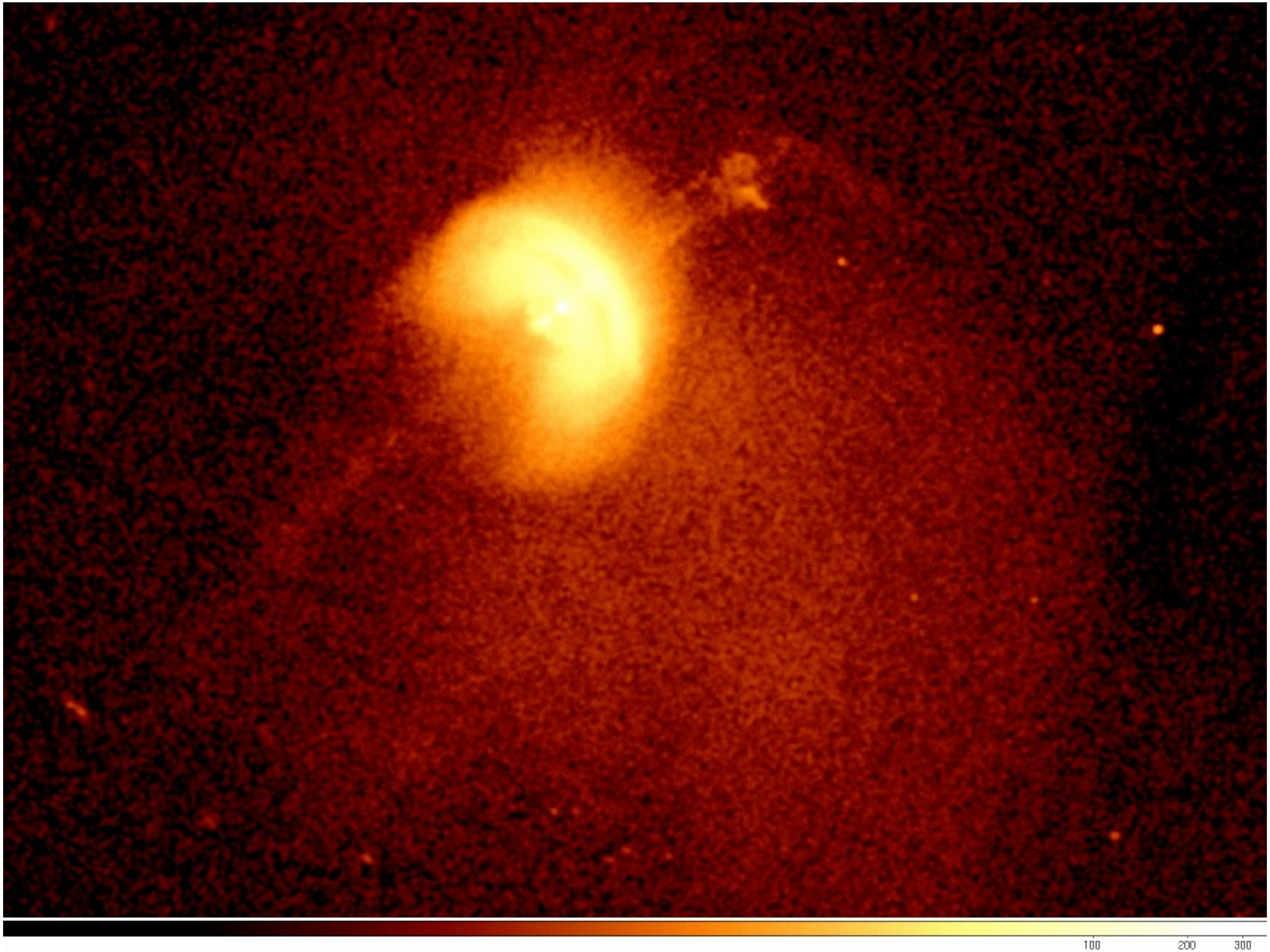


New observations of July 2009

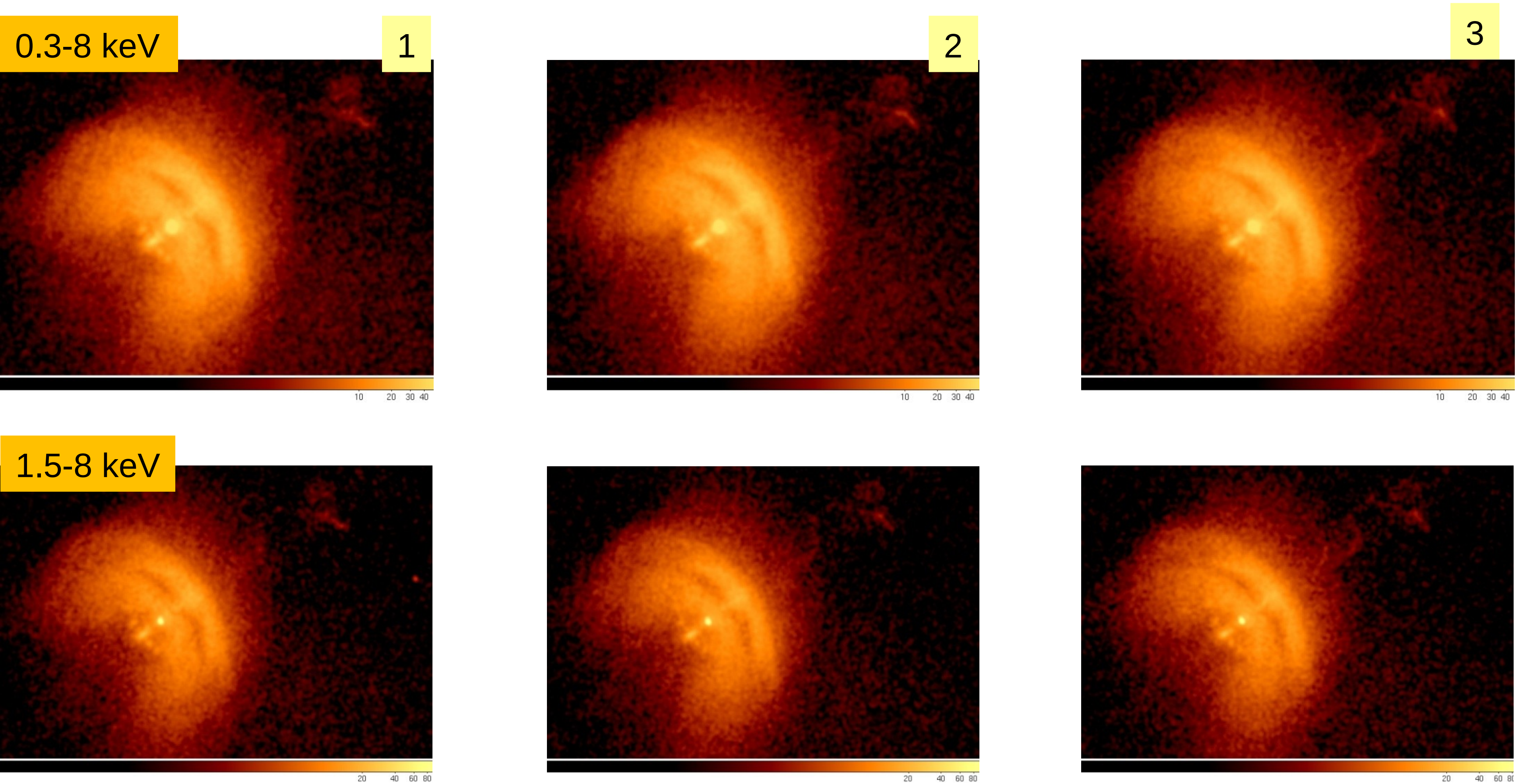
We proposed to observe the Vela PWN with ACIS in a sequence of **eight 40-ks observations** in July-August 2009, separated by intervals of ~8 days.

Because of technical issues,
only 3 observations were taken
(July 9, 16 and 25; 40+40+38 ks).

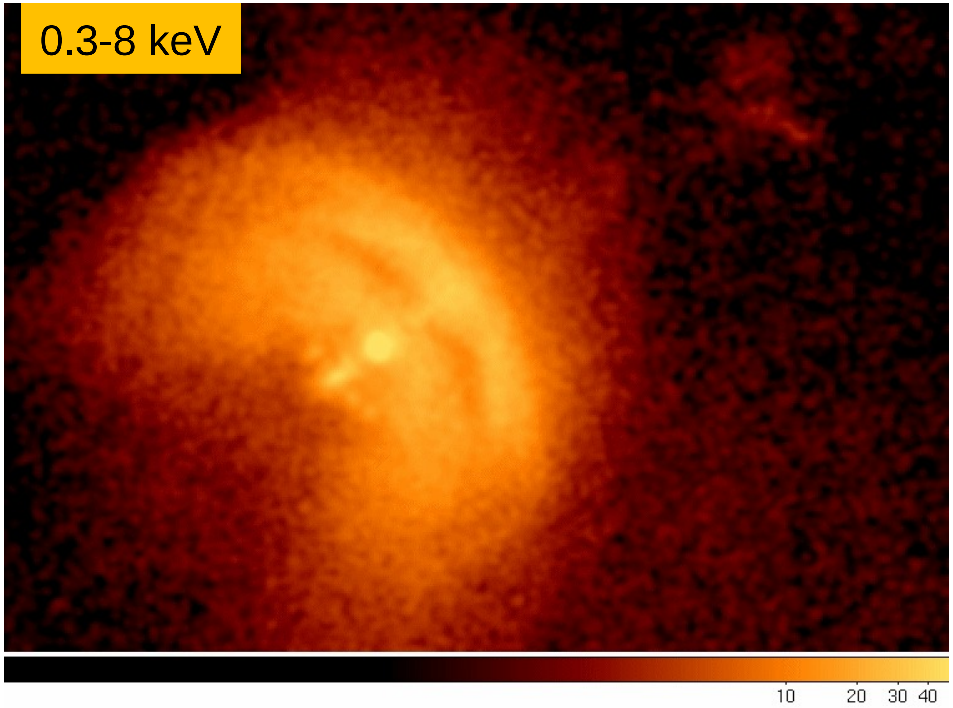
Sum of the 3 exposures: Varying the image brightness (118 ks, 1–8 keV)

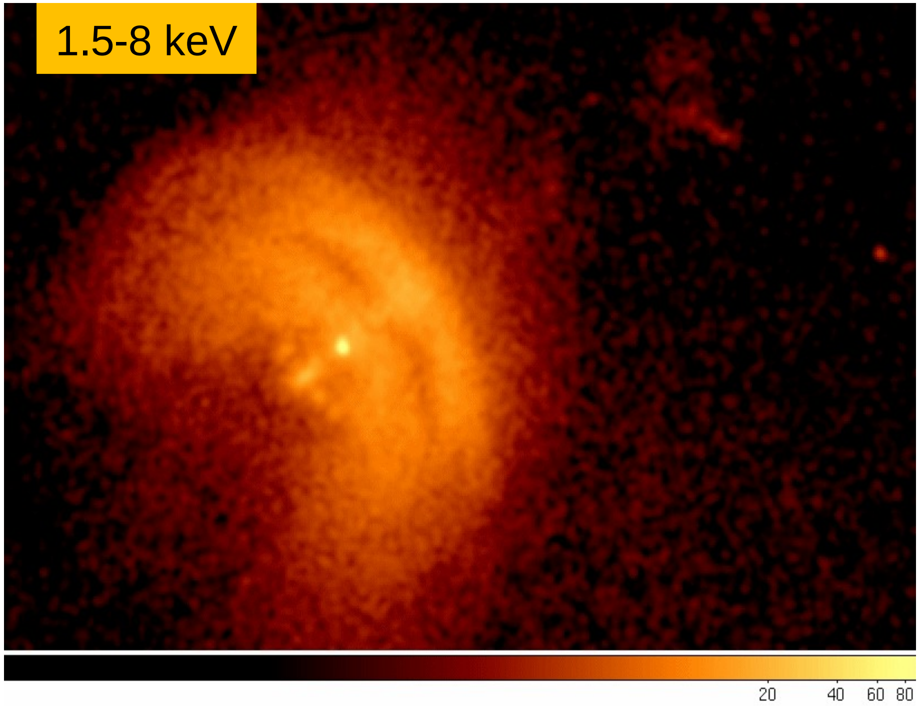


Three observations in different energy bands



Three-frame animations in two energy bands



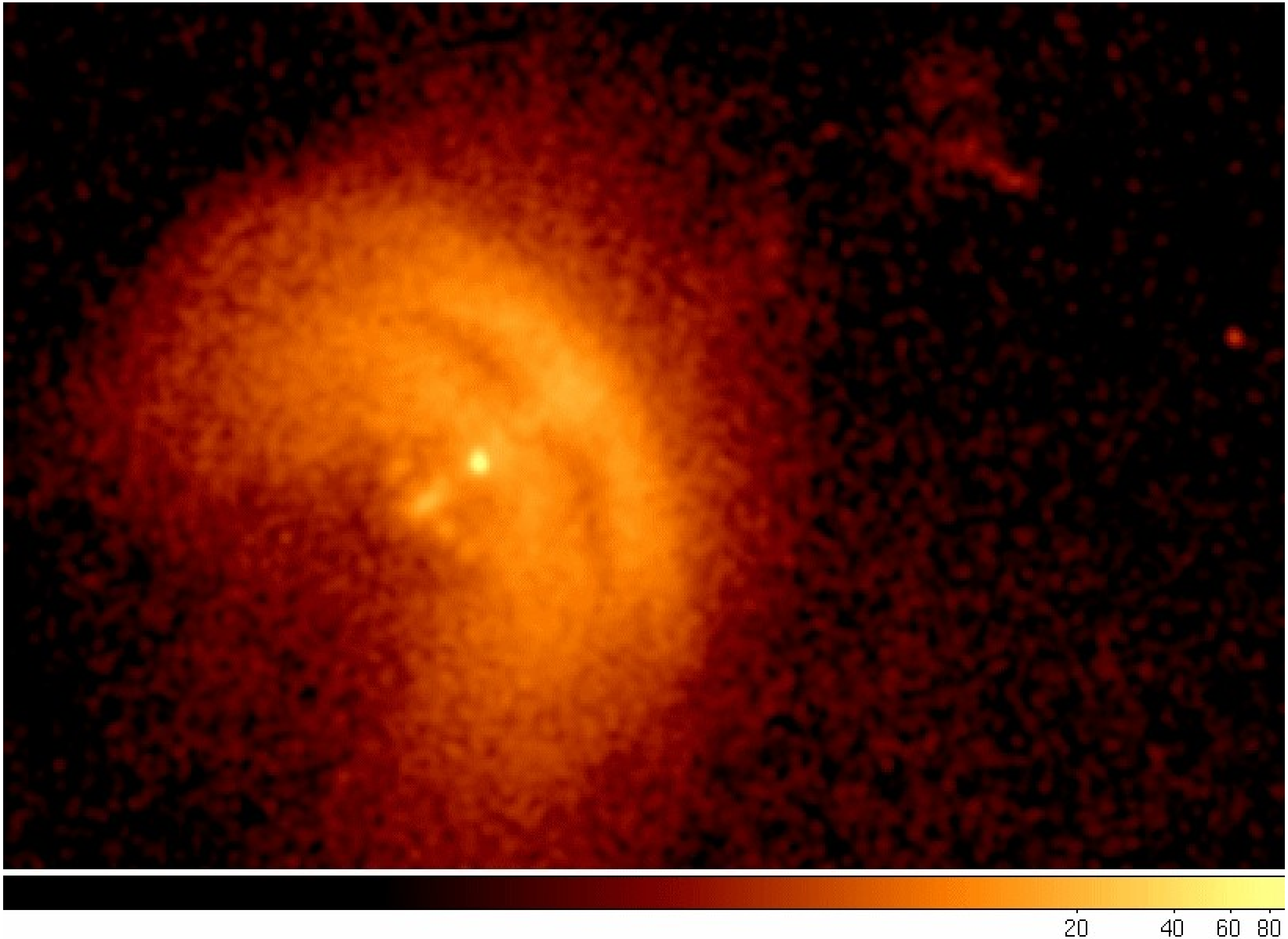


Changes are most prominent in the sickle-like outer jet (projection of a corkscrew?)

No moving blobs are seen in the outer jet.

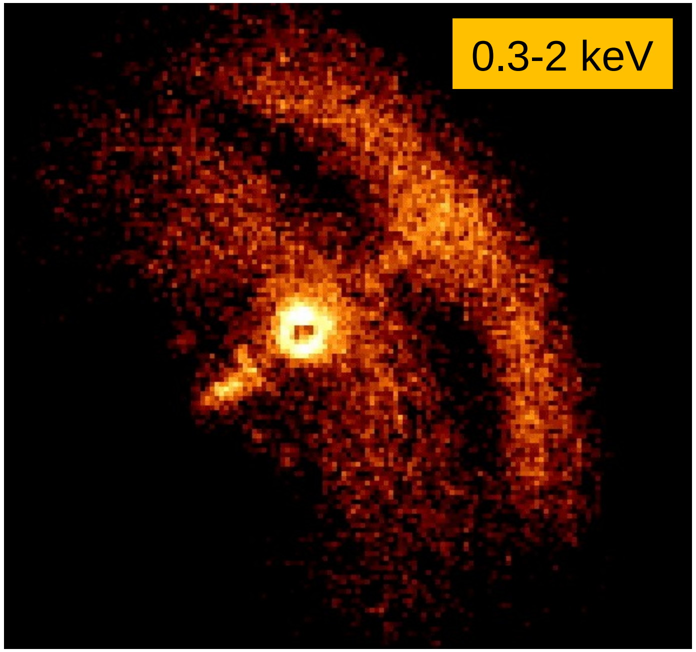
A strange extended structure near the apparent end of the outer jet.

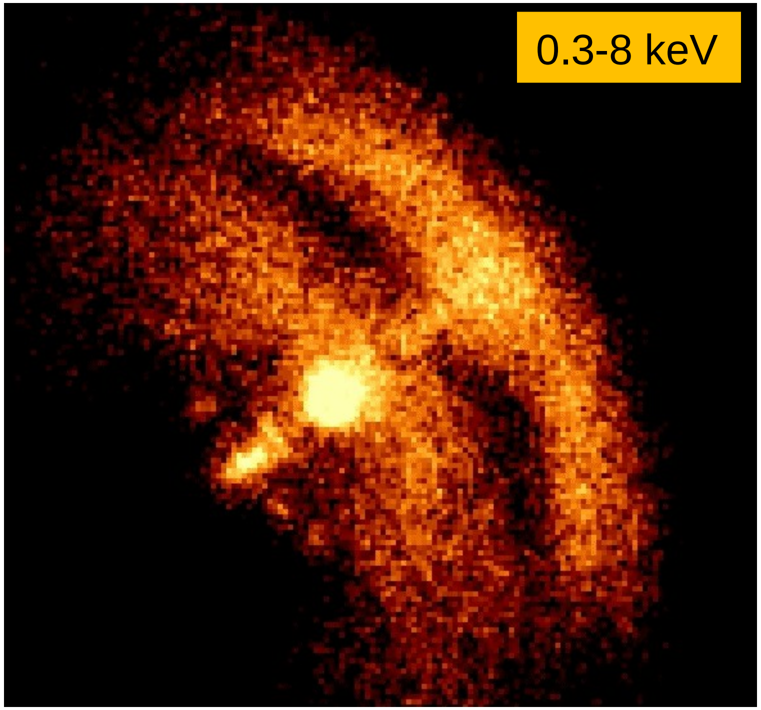
Two-frame animation (first and third frames) in 1.5–8 keV

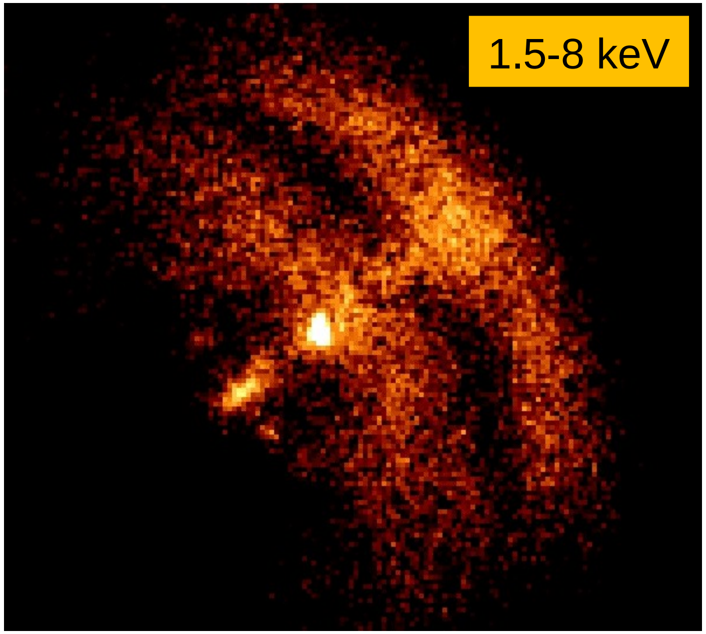


Three-frame animation of the brightest central part in 3 energy bands

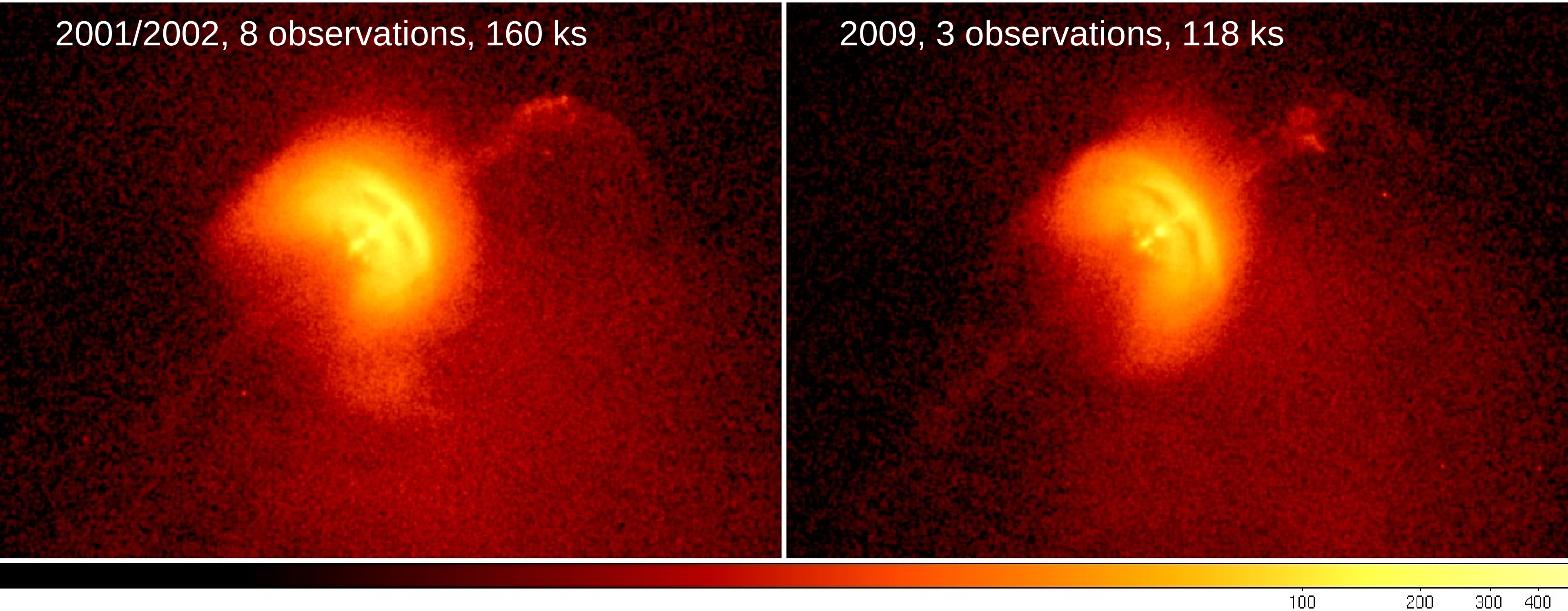
Changes most pronounced in the “bar” and “knots” on the back side of the ring (dark continuation of the Inner Arc).







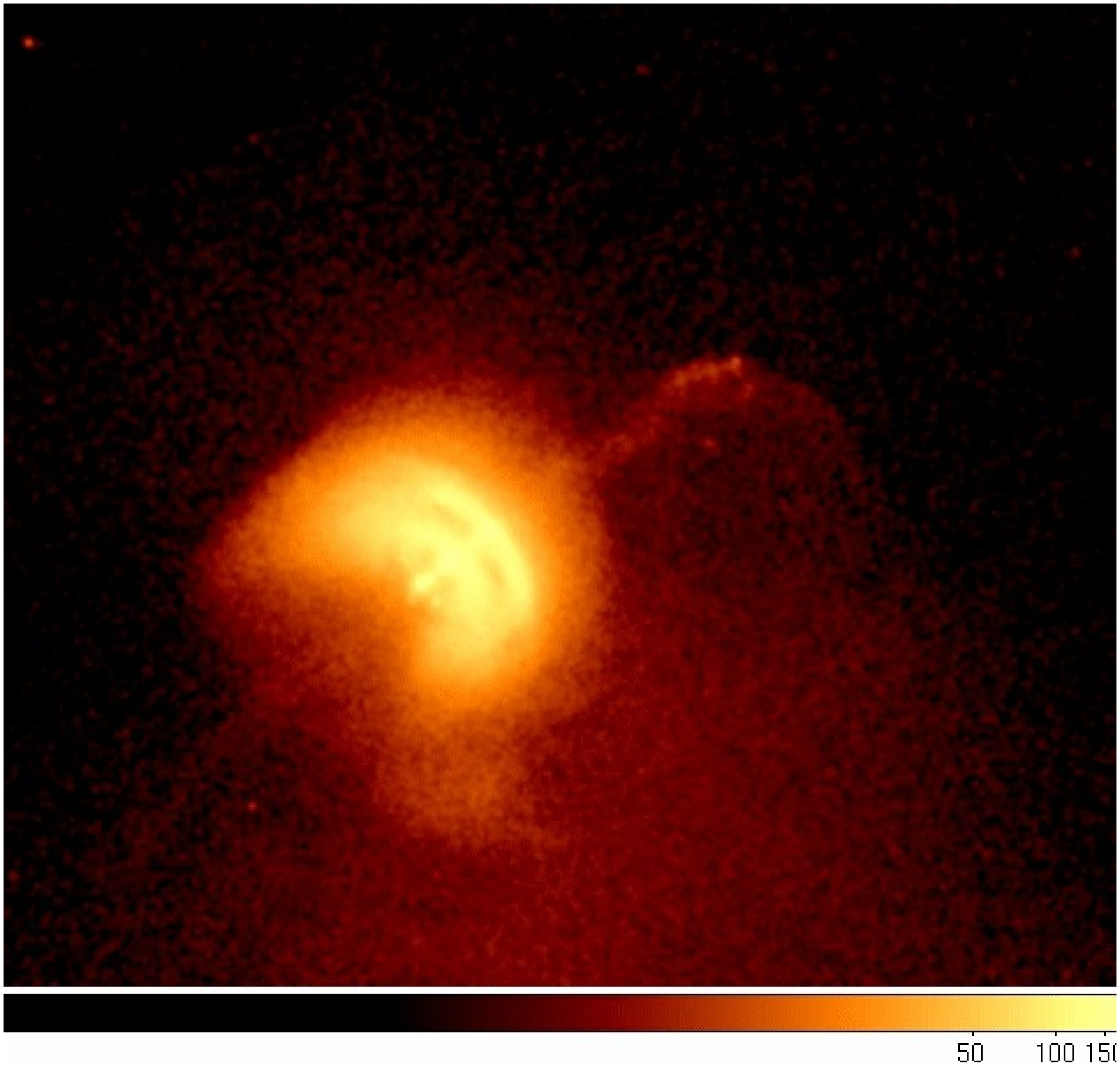
Comparing PWN images in two epochs



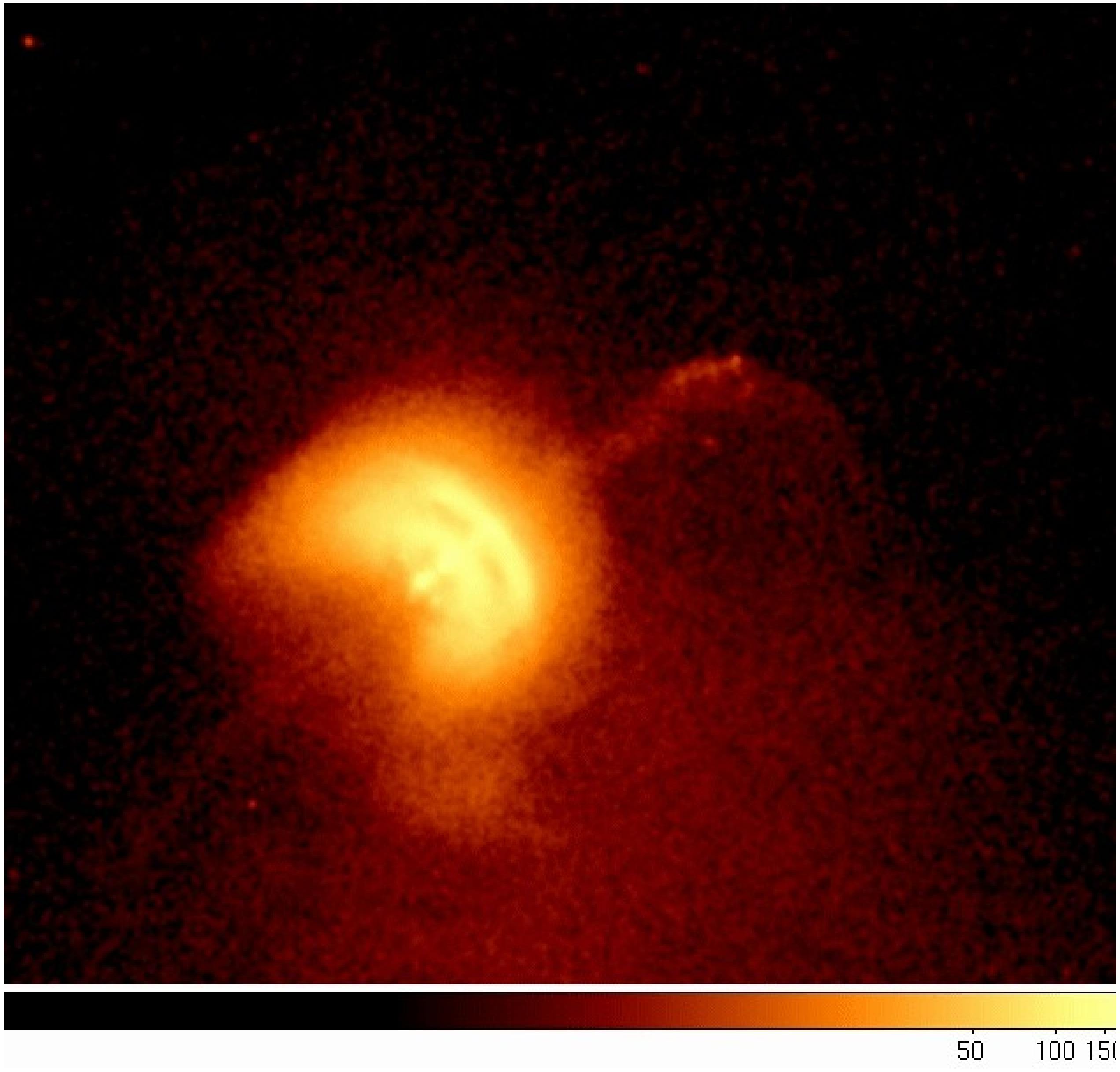
Different cumulative images of the outer jet.

Different shapes of the compact PWN (the shell has shrunk, changed the shape)

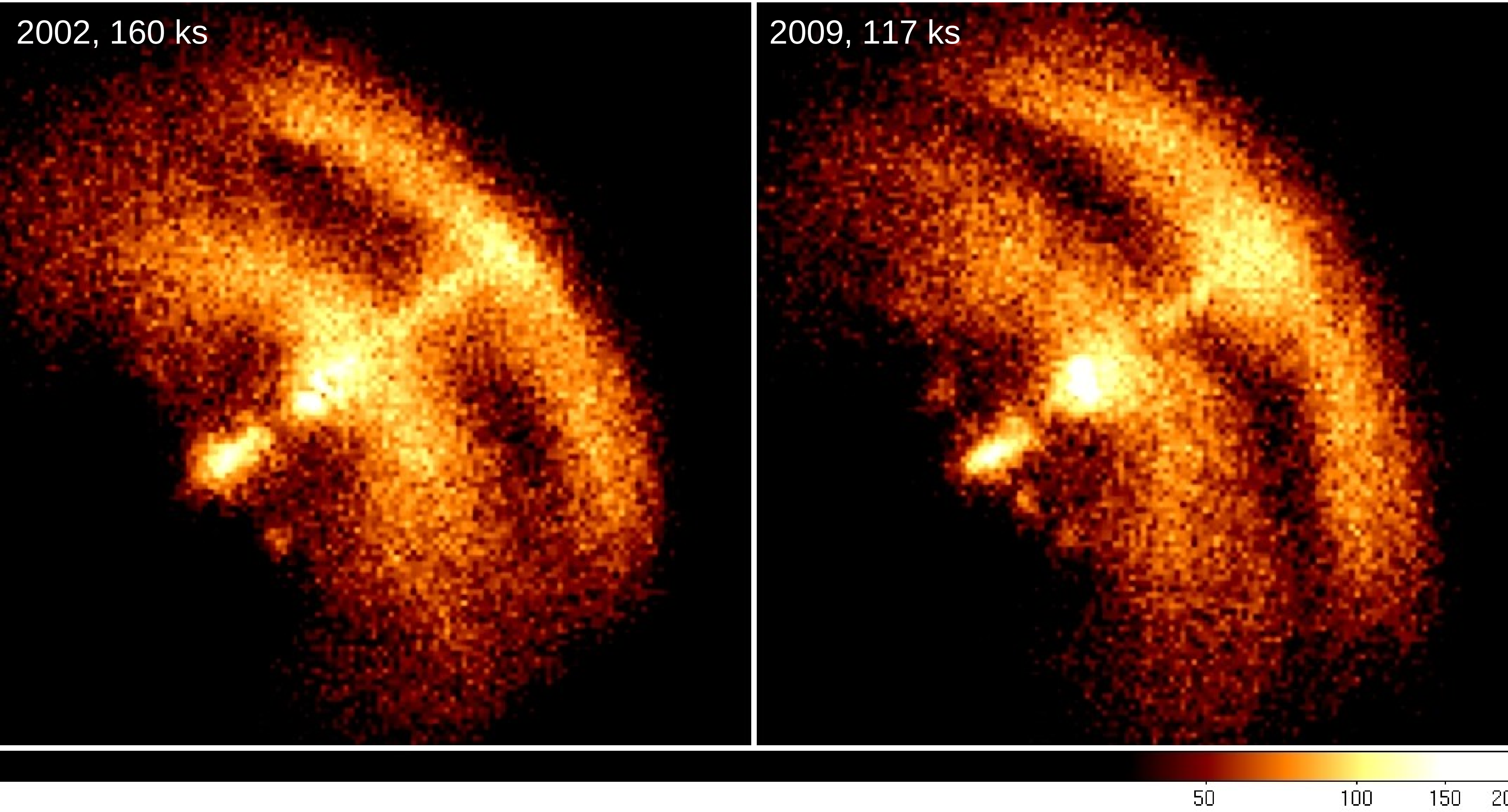
2009 versus 2001/2002: Two-frame animation; 1.5 – 8 keV



2009 vs 2001/2002: Two-frame animation with an artificially smooth transition

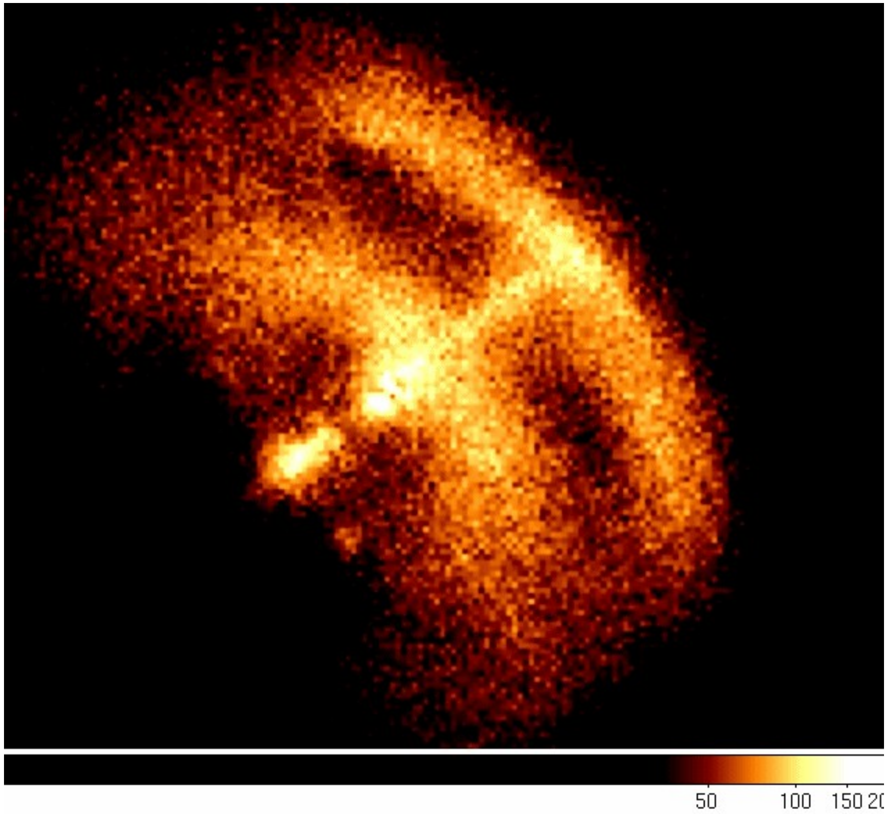


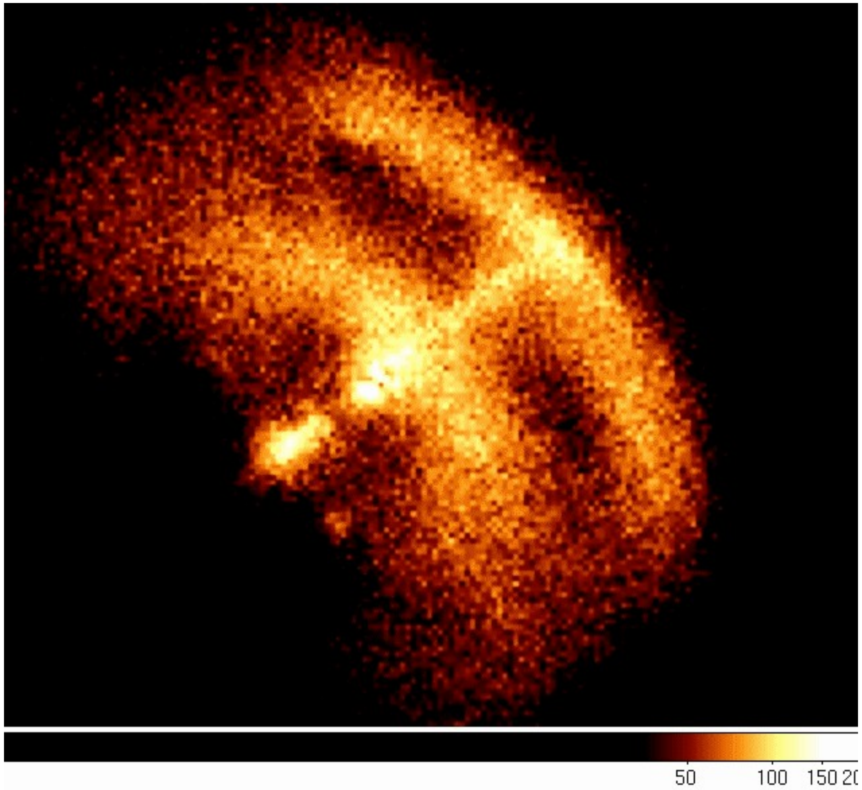
Comparing epochs 2002 and 2009



2001/2002 versus 2009 for the bright inner PWN

Two-frame animations without and with artificially smooth transition. The two frames are registered with a better than 0.3 arcses precision wrt background sources. (PSR has shifted by 0.41'' in 7 years.)





The radius of the Inner Ring increased; the knots on its dark side changed their positions.

The Outer Arc has moved forward by a few arcseconds. → More rarefied ambient medium?

Color-coded image of the bright inner PWN in two energy bands: 0.3 – 1.5 kev (red) and 1.5 – 8 keV (blue)

278 ks of data
(2001/2002 + 2009)

The PWN spectrum is harder than the pulsar’s spectrum

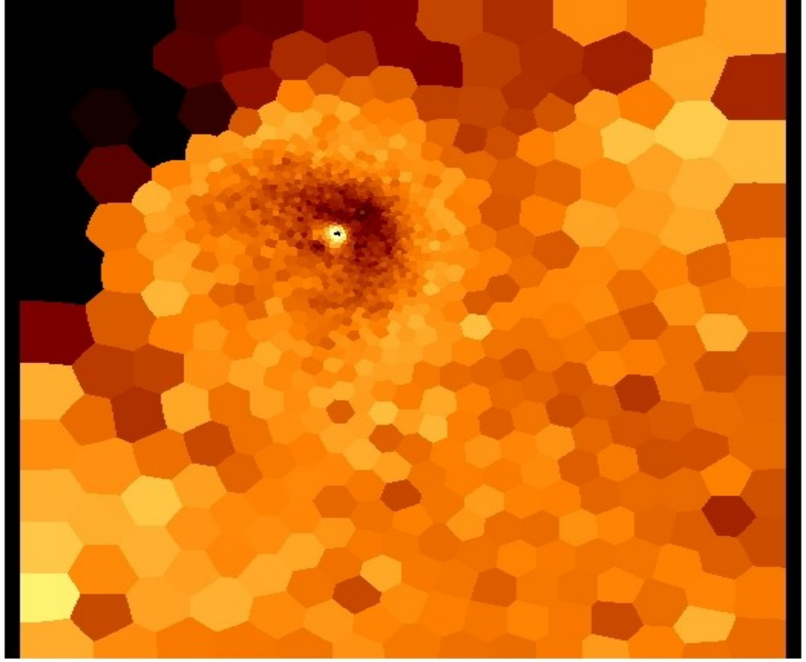
The spectrum of Outer Arc is softer than that of the Inner Arc

The spectrum of NW jet is harder than that of SE jet

Quantitative analysis requires a spectral map

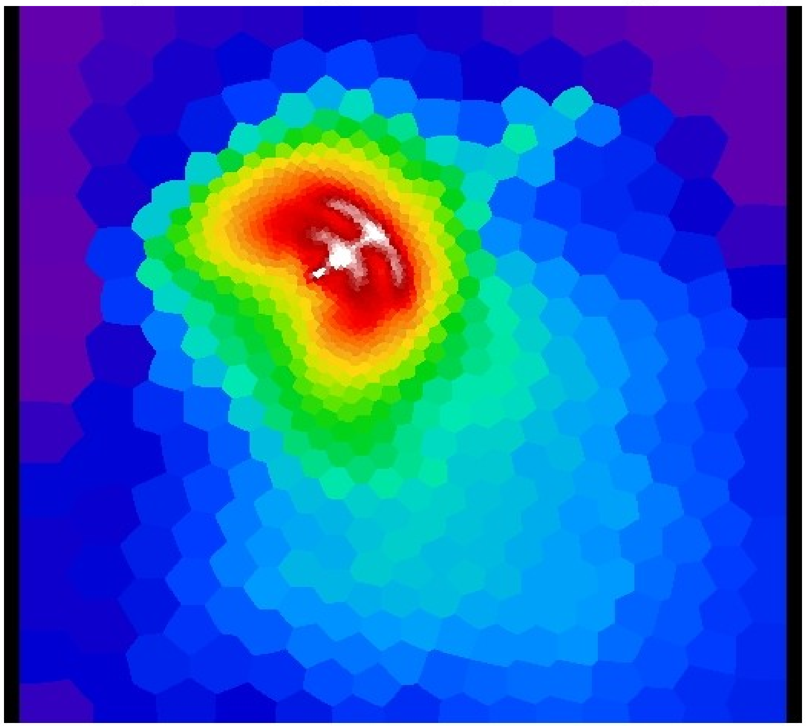
Data of 2001/2002 (160 ks) + 2009 (118 ks)

Adaptively binned brightness image (bottom) and **map of photon index Γ** (top), with the same bin sizes.



The inner PWN's spectrum is particularly hard, Γ = 1.0 – 1.3 (+/-0.03 uncertainty), as well as the spectrum of the Outer Jet

The hard-spectrum inner PWN is surrounded by a soft-spectrum shell (Γ ~ 1.8).



The large-scale diffuse emission SW of the inner PWN is harder than the shell – fed through the outer jet?.

The very hard spectra of the inner PWN imply a very hard spectrum of the emiiting electrons: p = 2Γ -1 ~ 1 (instead of a typical p ~ 2 – 3, such as in the Crab PWN). **Requires an explanation**.

Conclusions

The Vela PWN apparently belongs to the same class of young, subsonically moving PWNe as the Crab PWN but shows significant differences from the Crab in morphology, dynamics and spectra

New observations of the Vela PWN (July 2009):

- Confirmed variability of the outer jet, and possibly of the knots and the bar, on ~1 week time scale.
- Showed a significant change of the compact PWN in 7 years – varying (nonuniform) ambient medium?
- Allowed us to construct the PWN spectral map with a high spatial resolution.

As only 3/8 of our Long Program have been carried out, we were not able to reach all the program's goals and answer many important questions about the Vela PWN.

We still do not understand the topology of the Vela PWN and the origin of some of its elements. For instance, what is the Outer Arc? What is the connection of the outer jet with the NW inner jet? What are the knots? Why is the Vela PWN so X-ray inefficient? Why is its spectrum so hard? Etc…

We expect to answer at least some of the questions when our program is completed (tentatively scheduled for January-February 2010).