The Multi-Scale Structure of the J1809-1917 Pulsar Wind Nebula

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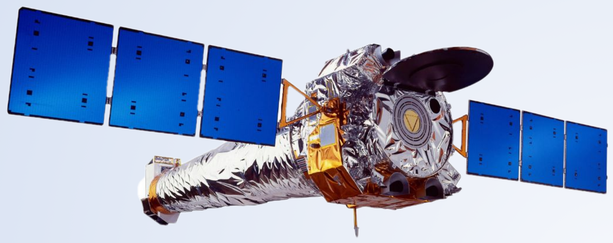
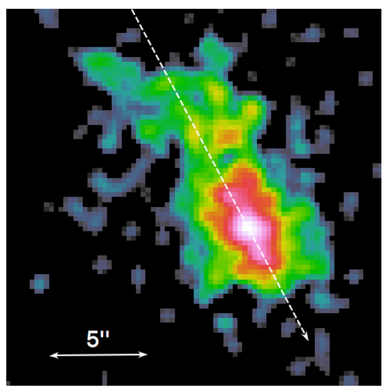


ABSTRACT

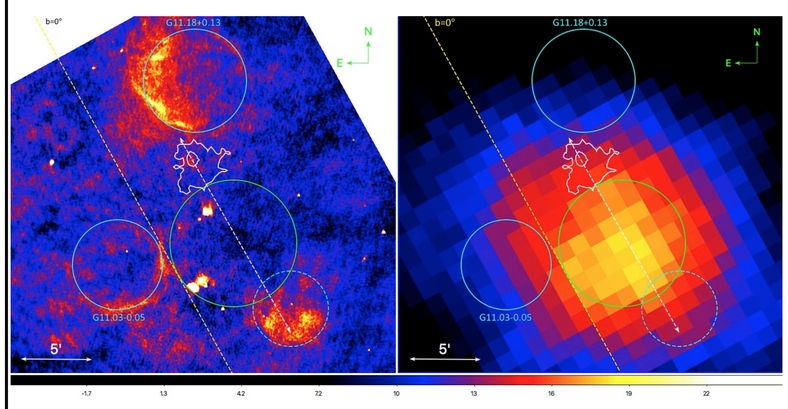
PWNe are sources of nonthermal X-ray emission and prominent sites of particle acceleration. PSR J1809-1917 is a young energetic radio pulsar powering a dynamic X-ray PWN. The nearby larger extended TeV source HESS J1809-193 is considered to be a relic PWN of PSR J1809-1917. We report the results of a CXO monitoring campaign consisting of 6 epochs spaced with 7-week intervals. The compact nebula changes in morphology and brightness across timescales of months. A bright clump of X-ray-emitting plasma, comparable in luminosity to the pulsar itself, moves on the same timescales -- likely the Doppler-boosted portion of a jet changing its orientation. The dynamics of the clump is not consistent with simple steady motion and is reminiscent of the variable Vela pulsar jet. The deep exposure obtained of combined new/archival data (540 ks) reveals an arcminute-scale bow-shaped structure aligned with the compact nebula's symmetry axis and pointed away from the HESS J1809. We detect an elongated asymmetric outflow, another instance of a kinetic jet: a stream of high-energy particles leaking from the bow shock.

PSR J1809–1917

- $\dot{E} = 1.8 \times 10^{36}$ erg s^{-1}
- DM = 197.1 pc cm^{-3}, d_{DM} ~ 3.3 kpc
- P = 82.7 ms
- τ_{SD} = 51.3 kyr
- $B_{surf} = 1.5 \times 10^{12}$ G
- Only radio pulsations detected
- 2.5 – 8 keV *Chandra* image revealed hard (Γ=1.2) 2”-scale jets oriented along axis of symmetry and toward HESS J1809–193.



- Radio (left), TeV (right) images:

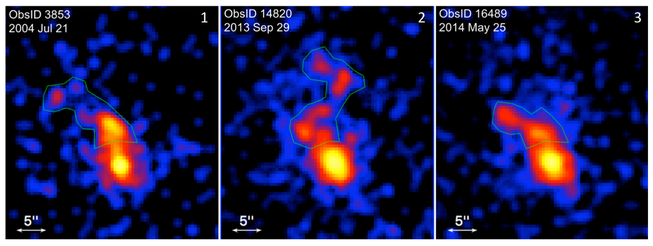


White contours -- J1809-1917 X-ray PWN, dashed white line -- symmetry axis of PWN/jets, green circle -- HESS J1809-193 center, cyan circles – SNRs (dashed circle – SNR candidate).

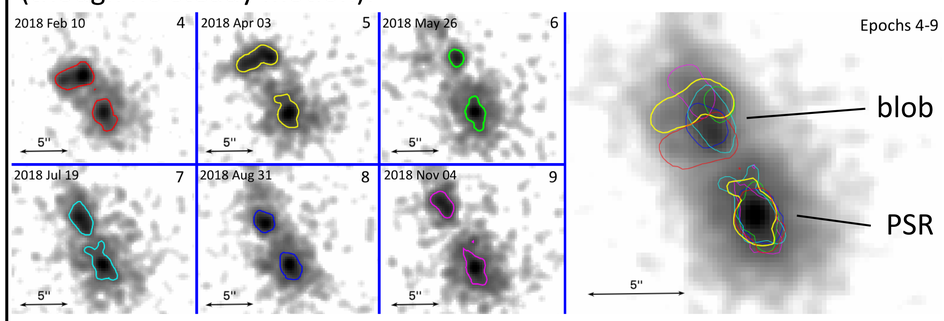
- Proper motion measured using all *CXO* obs: $\mu_{\{RA,dec\}}$ = {5 ± 10, 25 ± 13} mas/yr; corresponds to {78 ± 156, 390 ± 200} km/s; consistent with motion away from TeV source.

COMPACT NEBULA

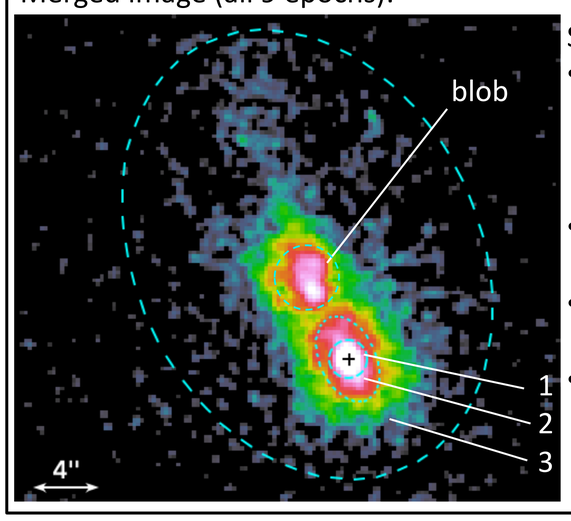
Archival observations: variability resembles wagging “fish tail” or tadpole



New observations: morphology has changed, compact nebula (CN) consists of bright “blob” 5 arcsec northeast of pulsar, position varies (though no steady motion):



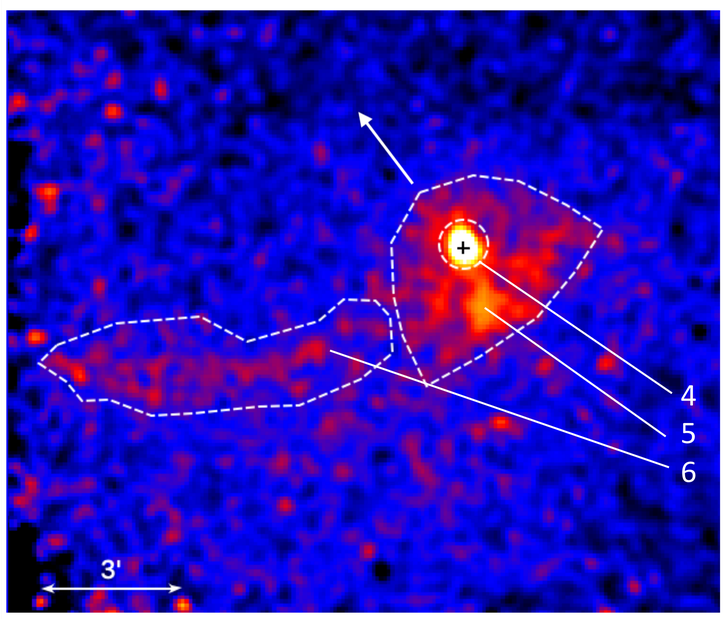
Merged image (all 9 epochs):



Spectra (for $n_{H,22}$ = 0.7 cm^{-2}):

- (1) PSR: Γ = 1.28 ± 0.15, + kT = 0.19 ± 0.03 (hot polar cap, 2.2 ± 0.4 MK)
- (2) Jets: Γ = 1.23 ± 0.09
- Blob: Γ = 1.34 ± 0.06
- (3) Compact Nebula: Γ = 1.52 ± 0.03

EXTENDED NEBULA



Spectra:
(4) CN vicinity: Γ = 1.72 ± 0.08

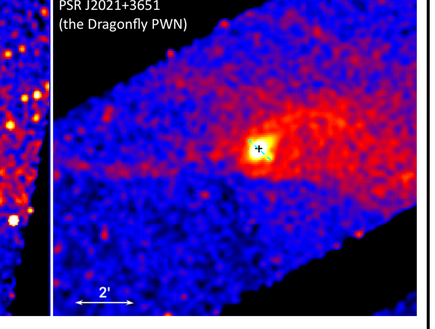
(5) Ext. nebula: Γ = 1.74 ± 0.05

(6) Outflow: Γ = 1.74 ± 0.12

- Deep merged image (540 ks) reveals a dome-shaped extended nebula with a large apex distance (1.5’).
- This suggests that J1809 is a transonic PWN whose morphology is shaped by ram pressure (Mach number $\mathcal{M} = v_{PSR} / c_{ISM}$ ~ 1).
- Another “misaligned outflow” / “kinetic jet” is seen extending ≥7’ from the EN (limited by the ACIS FOV).

DISCUSSION

- PWN morphology and measure motion are consistent with association with HESS J1809-193.
- CN morphology: bent jet is Doppler-boosted toward observer at point (D), appears (in projection) as a brightened “blob” ahead of the pulsar (point B).



This small-viewing-angle geometric interpretation is consistent with the lack of detectable γ-ray pulsations.

- Blob’s varying position can be caused by helicity or kink instabilities (similar to Vela jet; Pavlov+03), variable jet strength, or nonuniformities in ram / PWN pressure.
- Large apex distance (r~1.5’) suggests transonic pulsar motion (Mach number $\mathcal{M} \equiv v_{PSR} / c_{ISM}$ ~ 1; v_{PSR} ~ a few × 10 km/s), and low number density (n ~ 0.01 cm^{-3}). Morphology and apex comparable to other transonic PWNe:

- “Misaligned outflows” / “kinetic jets” are typically formed in nebulae of fast-moving PSRs when Larmor radii of high-E e$^-$ exceeds bow shock stand-off distance (Bandiera 08), and/or via reconnection of ISM and PWN magnetic field lines (Barkov+19, Olmi & Bucciantini 19). Kinetic jets in transonic PWNe serves as evidence for the latter scenario.
- Misaligned outflows are expected to be less luminous than the tails of their associated pulsars, since only a fraction of the pulsar wind escapes into the outflow, with most of the wind flowing through the tail. However, this may depend on the Mach number, or other factors. (Note that the Guitar PWN lacks a tail altogether, despite having a large Mach number.)