Misaligned Outflows in Pulsar Wind Nebulae

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Abstract

This poster offers an introductory exploration of misaligned outflows in pulsar wind nebulae (PWNe), a phenomenon where the outflows are not aligned with a reference direction, such as the pulsar's velocity vector. These misalignments, observed in several PWNe, provide insights into the nebulae's morphology and evolution, including particle acceleration mechanisms, magnetic field geometry, and the interaction of the wind with the surrounding environment.

1 Observational Properties

- Linear Morphology: long, narrow nonthermal filaments, extending far beyond the PWN's main body.
- Misalignment: Significantly deviate from the pulsar's velocity vector.
- Asymmetry: often more extended in one direction.
- Spectral Softening: Some X-ray spectra soften with increasing distance from the pulsar.
- Magnetic Field Interaction: Outflow morphology suggests interaction with and illumination of pre-existing interstellar magnetic fields.

We present misaligned outflows as two types: confirmed outflows and possible outflows.

2 Confirmed Misaligned Outflows

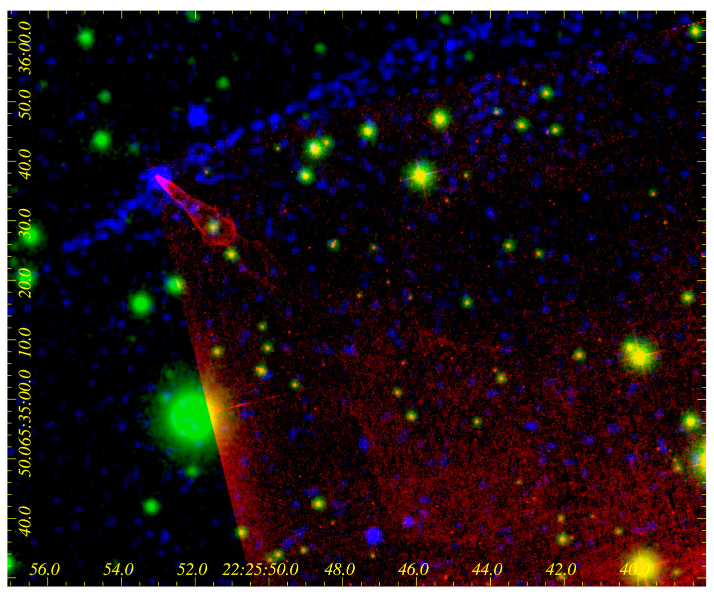

Figure 1: The field of PSR B2224+65 (Guitar). Red: HST Hα, blue: Chandra keV X-rays. The pulsar point source lies at the tip of the Hα nebula. The image is from de Vries et al. (2022).

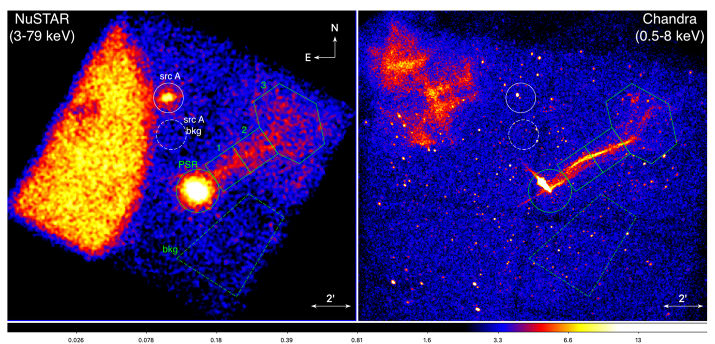

Figure 2: NuSTAR and Chandra image of PSR J1101−6101. The image is from Klingler et al. (2023).

Figure 3: Field of PSR J1509-5850: Image credit: X-ray: NASA/CXC/George Washington Univ. Klingler et al. (2016a); Optical: DSS; Radio: CSIRO/ATNF/ATCA.

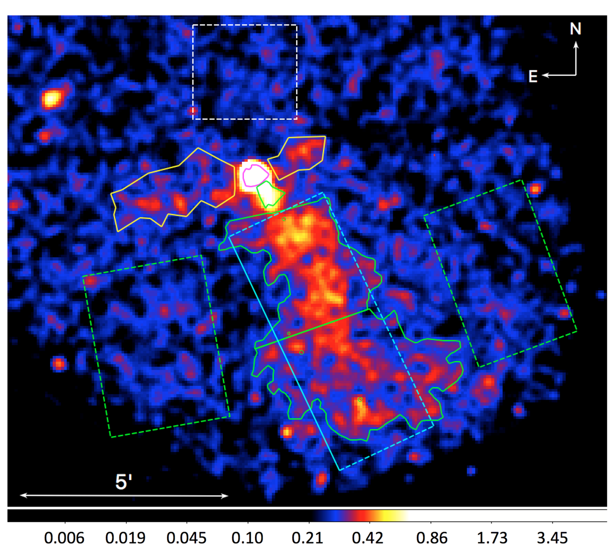

Figure 4: Chandra X-ray image of PSR B0355+54 from Klingler et al. (2016b). There is prominent misaligned outflow nearly perpendicular to pulsar proper motion.

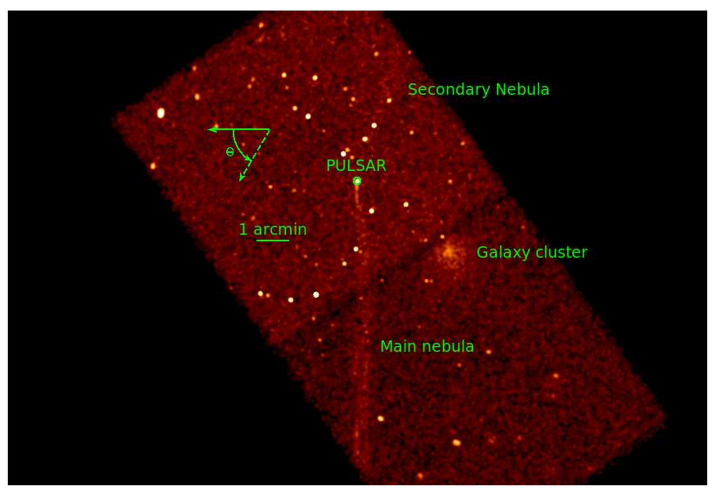

Figure 5: Chandra image of PSR J2055+2539. The positions of the pulsar is labeled. From Marelli et al. (2019)

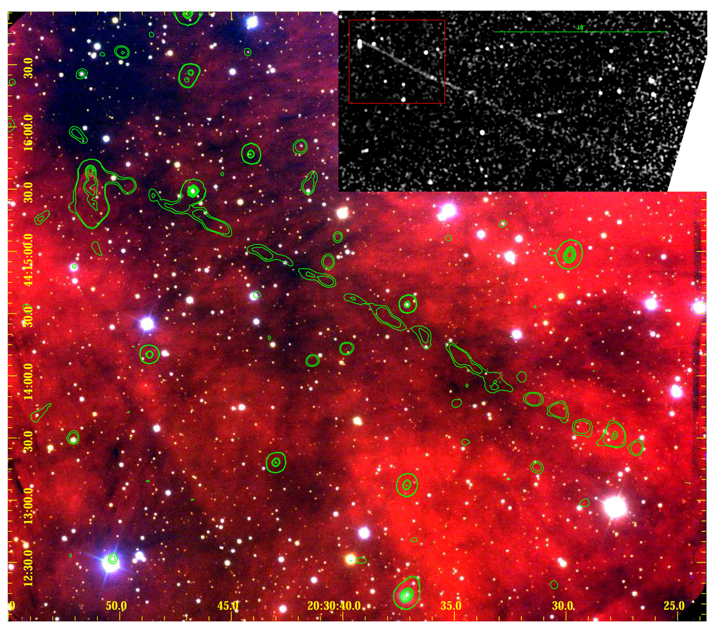

Figure 6: The PSR J2030+4415 field in GMOS-N Hα (red), r (green), and g (blue). The smoothed green contours show 1–5 keV CXO ACIS emission; the PWN and filament are visible. The gray scale inset at upper right shows the combined ACIS data following the filament's 15′ length. Figure is from de Vries & Romani (2022).

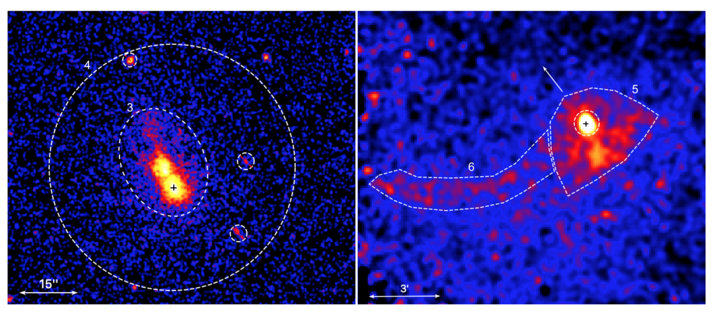

Figure 7: Merged exposure-map-corrected ACIS image (540 ks) of the J1809-1917 extended nebula. The misaligned outflow is labeled 6. Figure is from Klingler et al. (2020).

3 Possible Misaligned Outflows

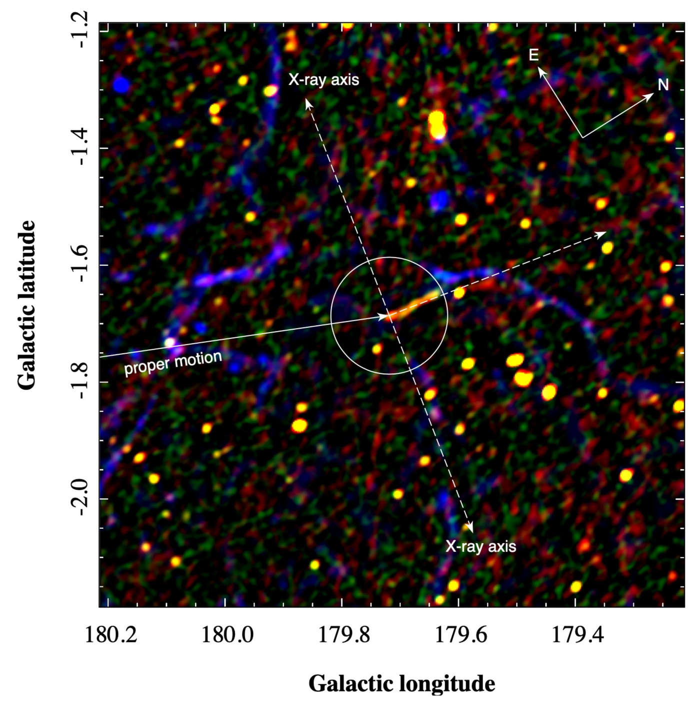

Figure 8: Non-thermal radio filament of ahead of PSR J0538+2817. From Khabibullin et al. (2023).

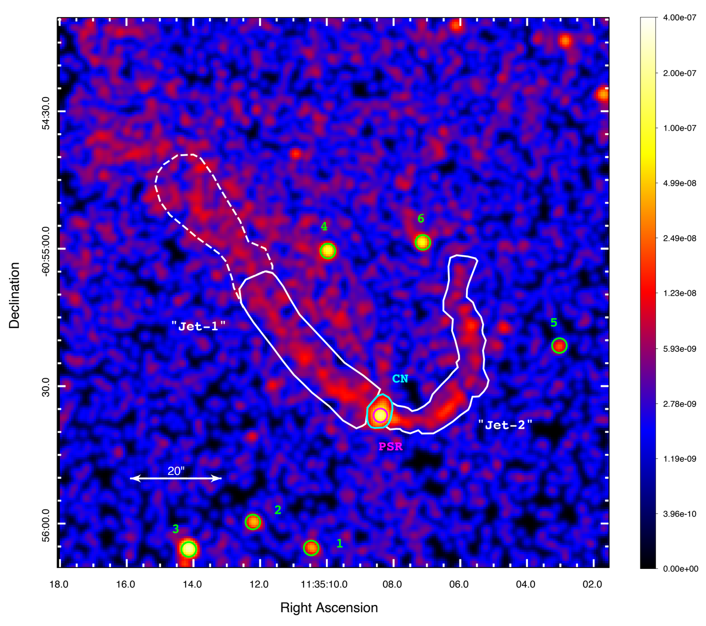

Figure 9: Chandra exposure-corrected flux map of the extended emission around PSR J1135-6055 for energies in the range 0.5-7.0 keV. From Bordas & Zhang (2020).

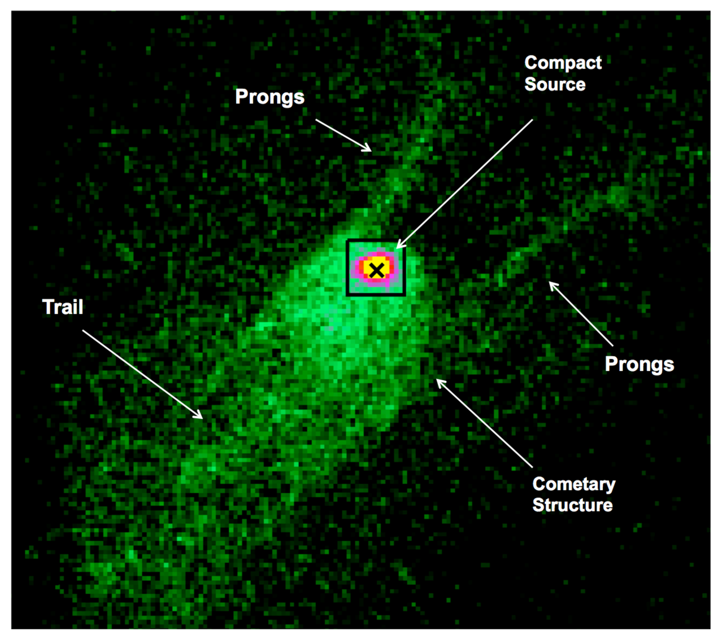

Figure 10: Chandra ACIS image of G327.1-1.1 (Snail) region. Nonthermal pronts like structure. From Temim et al. (2015).

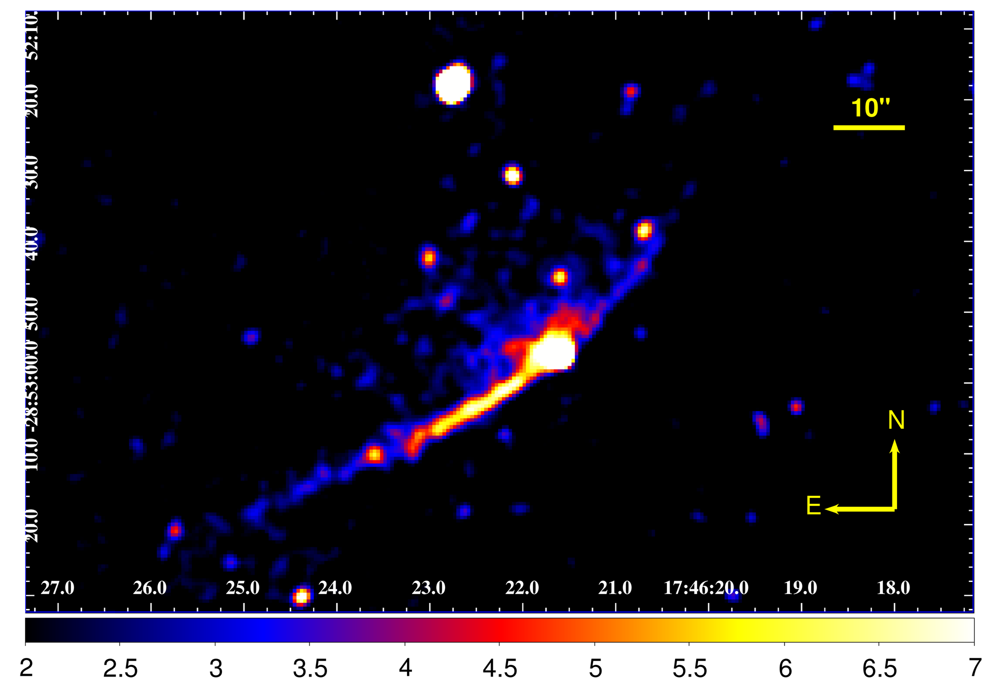

Figure 11: Chandra mosaic of the region surrounding nonthermal X-ray filament G0.13-0.11. From Zhang et al. (2020)

4 Theoretical Models

1) **The kinetic streaming model:** high-energy electrons with gyroradii comparable to the bow shock size leak into the ISM, producing the observed X-ray features.
   Pros: Explains the linear morphology and misalignment seen in outflows like the Guitar Nebula.
   Cons: Requires amplification of the ISM magnetic field to explain the observed X-ray brightness and narrow profile.
2) **Non-resonant streaming instability (NRI)**: charge-separated electrons and/or positrons escaping the PWN, likely through reconnection regions between nebular and interstellar magnetic fields, drive the NRI.
   Pros: Naturally explains the filament length as a consequence of the ballistic propagation of escaping particles before the instability saturates.
   Cons: Requires a charge-separated outflow, placing stringent limits on the number of particles with energies close to the pulsar's maximum potential drop.

5 Future Research Directions

Future research directions on misaligned outflows in PWNe must address several key areas:

1) Need for further observations: deeper and higher-resolution, multi-wavelength studies and polarization measurement.
2) Development of more refined theoretical models

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