Spatially-resolved Spectroscopy of the IC443 Pulsar Wind Nebula and Environs

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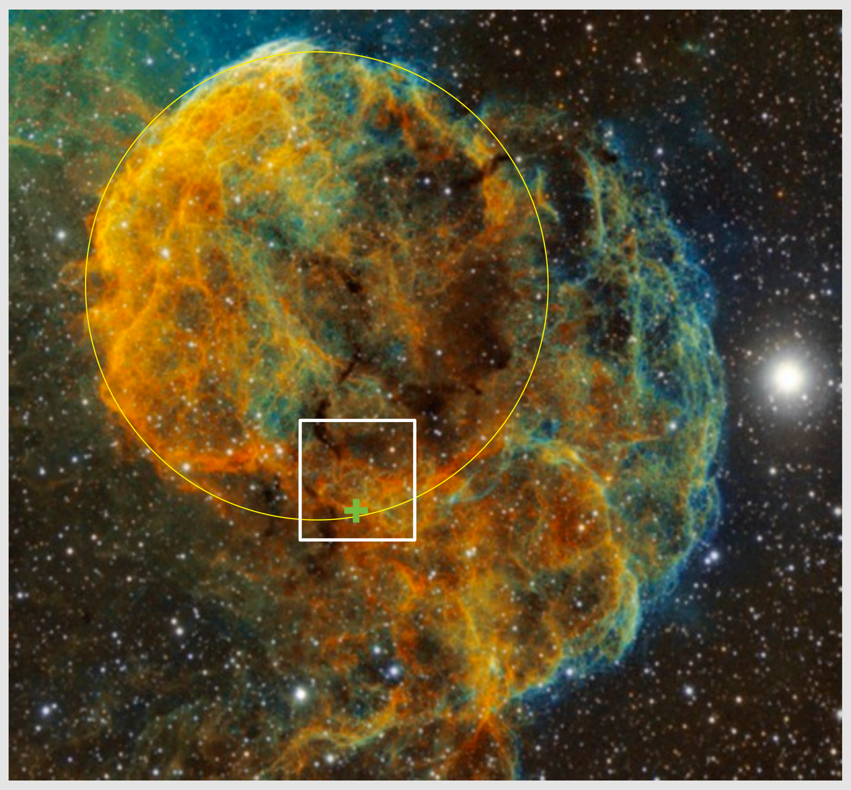
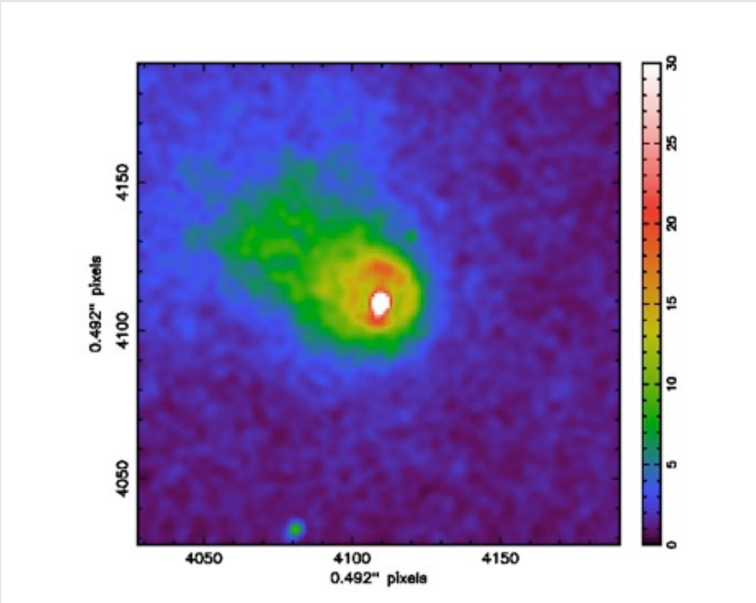
Deep Chandra ACIS observations of the region around the putative pulsar, CXOU J061705.3+222117, in the supernova remnant IC443 reveal, for the first time, a ring-like morphology surrounding the pulsar and a jet-like structure oriented roughly north-south across the ring and through the pulsar location. The observations further confirm that (1) the spectrum and flux of the central object are consistent with a rotation-powered pulsar interpretation, (2) the non-thermal surrounding nebula is likely powered by the pulsar wind, and (3) the thermal-dominated spectrum at greater distances is consistent with emission from the supernova remnant. The cometary shape of the nebula, suggesting motion towards the southwest (or, equivalently, flow of ambient medium to the northeast), appears to be subsonic; there is no evidence for a strong bow shock, and the circular ring is not distorted by motion through the ambient medium.

Introduction

IC443 is a large supernova remnant, roughly 1500 pc distant, in the constellation Gemini. We obtained a deep, 152 ks, *Chandra* ACIS-S image of a portion of the remnant (white square in the image at right) containing the bright X-ray source CXOU J061705.3+222127 in order to study this source and its surroundings. The source is likely a pulsar (PSR) surrounded by a pulsar wind nebula (PWN). The circle shown at right roughly depicts a possible remnant shell although some material is breaking out to the S and W. The location of the PSR is of particular interest because it appears to be located where the remnant shell interacts with an ambient molecular cloud. This alignment suggests the system is entering a rare transitional stage where the overall shape of the PWN is affected by this interaction and/or by the supernova reverse shock.



IC443 image in [SII], Ha, and [OIII] (RGB) from Bob Franke's Focal Pointe Observatory (http://bf-astro.com/). Location of the 8'x8' Chandra/ACIS-S3 CCD is shown as a white square and the pulsar is marked by the green cross, A 30' diameter circle is shown for reference. North is up and east is to the left.



X-ray image of the region around the PSR in the 2-4 keV energy range. The image has been smoothed with two passes of a nearest-neighbor smoothing algorithm. Color scale is counts/pixel. The PSR and the southern extension of the jet-like feature appears white, the ring and northern jet are red, and the comet-shaped PWN extends to the NE in green and blue. North is up and east is to the left.

Our new *Chandra* observation reveals, for the first time, a ring-like morphology surrounding the pulsar and a jet-like structure oriented roughly north-south across the ring and through the pulsar's location. The ring is about 5″ in radius (0.1 ly) and ~2″ in width although the surface brightness varies azimuthally.

Exterior to the ring is a 2′x1.5′ comet-shaped nebula with its major axis oriented ~50^o E of N and with its apparent forward direction to the SW. Comparing this observation with historical observations, we set a 99% confidence upper limit to the proper motion of the PSR to be less than 310 km/s, with the best-fit (but not statistically significant) direction toward the west.

The cometary nebula has a hard X-ray spectrum while predominantly soft thermal X-ray emission surrounds the PWN and extends throughout the *Chandra* field of view. This soft emission is from the IC 443 SNR.

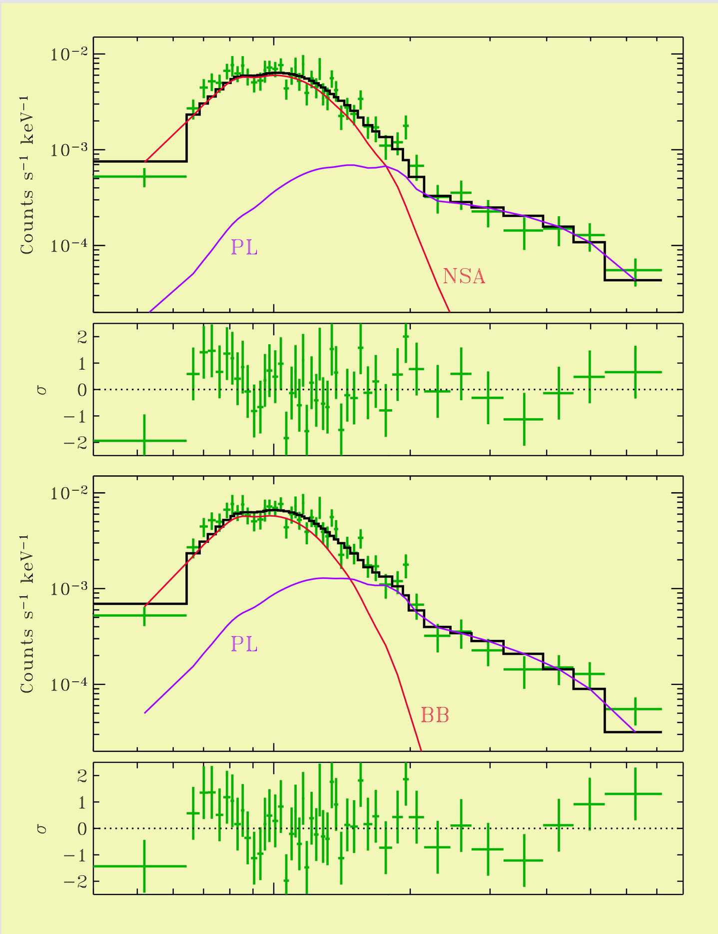
Is the Point Source a Pulsar?

We have fit models to the X-ray spectrum of the bright point source and find it is characteristic of a young rotation-powered pulsar. As shown at right, both an absorbed blackbody+power law and an absorbed neutron star atmosphere+power law provide statistically-acceptable fits to the observed spectrum. The table below shows the best-fitting model parameter values, the derived total X-ray luminosity (in the 0.5-8.0 keV range), and estimated spin-down luminosity, *dE/dt*, or rate at which the rotational energy is dissipated, relative to the Crab, assuming an efficiency of 10^{-4}. The 3.2 s time resolution is long to search for a period in the data but the spectrum and the bright non-thermal nebula indicate CXOU J061705.3+222127 is indeed a pulsar with a PWN.

Pulsar Spectral Fit Parameters

model	n_H (10^{21})	T (10^6)	L^{∞}_{bol} (10^{32})	Γ	L_X (10^{31})	$\dot{E}$ (Crab^a)
BB+PL	6.0	1.6	1.2	2.0	1.3	2.6×10^{-4}
NSA+PL	6.2	0.9	4.3	1.4	1.0	2.0×10^{-4}

^{a}where $\dot{E}_{Crab} = 5\times10^{38}$ and assumed $\eta = L_X/\dot{E} = 10^{-4}$



The X-ray shape and spectrum of the PWN

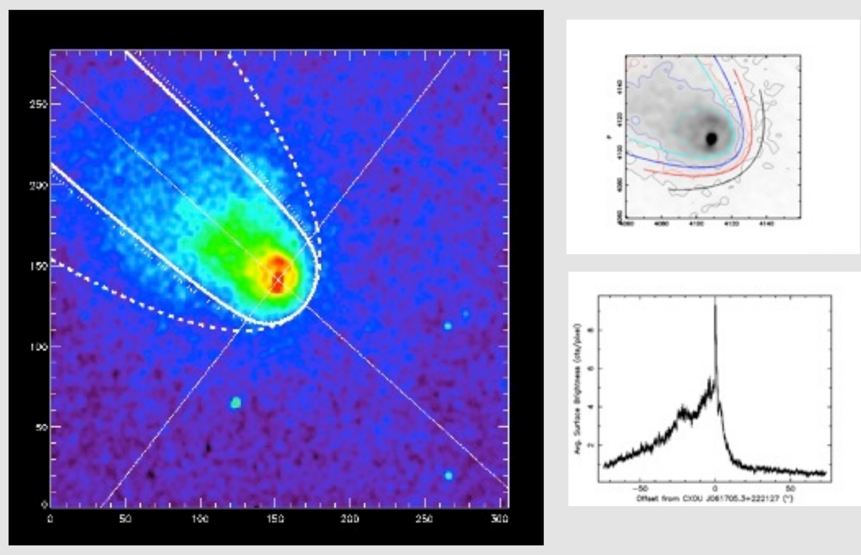
The pulsar emission geometry, magnetic field, and energy distribution as well as the properties of the ambient medium and the relative motion of the pulsar in that medium all determine the shape and spectrum of the PWN. In our case, most of these properties are unknown, and we must use the shape and X-ray spectrum to infer what we can about the pulsar and its surroundings. For supersonic flow, we expect (going outward from the PSR) a wind termination shock (TS), a contact discontinuity between the shocked wind and the shocked ambient medium, and a bow shock separating shocked and unshocked ambient flow.

Is the flow supersonic or subsonic?

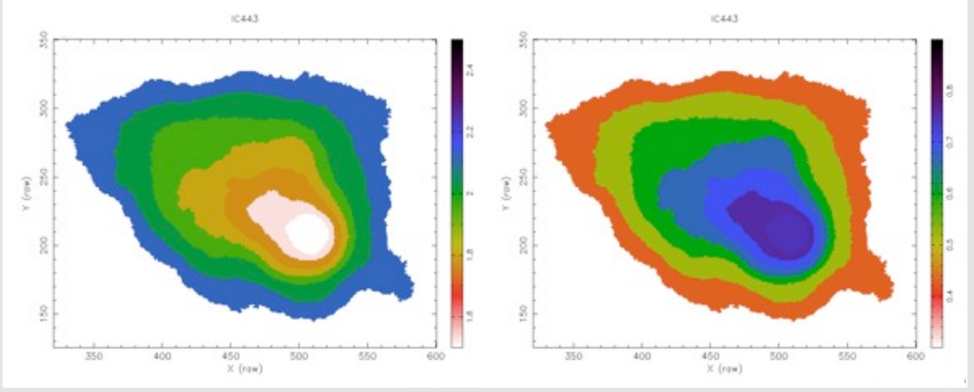
The cometary shape of the PWN suggests motion (on the plane of the sky) to the SW but this orientation is ~50^o away from the direction expected if the PSR originated in the center of the main (circular) IC 443 remnant to the North. Since the proper motion of the PSR is low, the most likely explanation for the cometary shape is a net flow of the ambient medium towards the NE, perhaps the reverse shock flow of the SNR.

We have estimated the shape of the head of the PWN, defined by the observed X-ray surface brightness contours, and compared it to analytical models of hypersonic (Wilkin 1996; Bucciantini 2002) and subsonic flow and found the shape is narrow indicating the flow is subsonic.

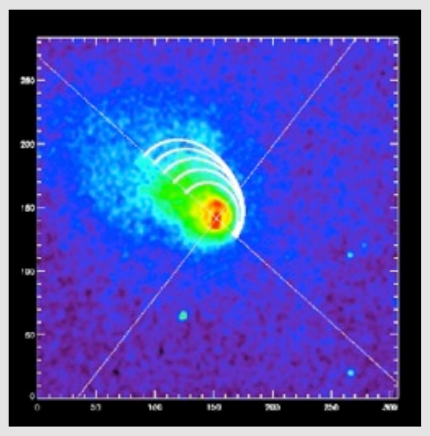
Analysis of the radial profile in the forward direction shows the X-ray surface brightness decreases exponentially with no clear transition from nonthermal wind to thermal shocked ISM, again indicating the flow is subsonic.



*Shape of the leading edge of the PWN. **Left**: Shape predicted by analytic models for supersonic (dashed line) and subsonic (solid line) flows. The supersonic case is determined by pressure equilibrium between the ram pressure of the ambient medium and that of the pulsar wind (Wilkin 1996). The subsonic case is the solution to Laplace's equation for the velocity field for a uniform flow along the cometary axis plus a radial flow diverging from the pulsar as $v\sim r^{-2}$. **Upper right**: Parabolas (heavy lines) approximating the observed X-ray surface brightness contours used to compare to the analytic models. **Lower right**: Brightness profile along PA 50^o through the PSR; 1′ width. Note the exponential drop off upstream (to the right), and the cometary extension downstream.*



Map of the X-ray power law spectral index (left) and flux (right; in units of 10^{-12} erg/cm^2/s) of the PWN. The pulsar is located at (x,y)=(510,205) and pixels are 0.492"x0.492". Note the softening (steepening) of the synchrotron spectrum outward from the PSR and the outward decrease in X-ray flux.



Left: Isochrone surfaces for the fully subsonic case. Shown are the locations within the nebula containing particles emitted by the PSR within the last 100, 200, 300, 400, and 500 yr assuming a flow speed of 1000 km/s (and scaling linearly with the flow speed). This model is consistent with the observed size of the PWN for standard synchrotron cooling and an equipartition B field strength deduced from the size and luminosity of the PWN (for a modest spin-down luminosity and magnetization parameter).

Synchrotron Cooling in the Tail

The PWN extends about 3 lyr (2′) downstream of the PSR. We used the contour-binning method of Sanders (2006) to subdivide the image into spatial bins of roughly constant X-ray surface brightness, then analyzed the spectra of these individual regions. We find the spectrum is dominated by a power law with spectral index decreasing (softening) from 1.5 in the ring to 2.2 at the outer edge of the PWN while the flux decreases smoothly outward. This is typical of synchrotron cooling in a subsonic flow of order a few 100 km/s where the cooling time is of order τ_{cool}~200 (B/70μG)$^{-3/2}$ yr at ~1 keV, where B is the magnetic field strength. In the supersonic case, the flow speed would be of order $c/2$ and the tail would extend much further downstream. A relative velocity of a few 100 km/s is consistent with our measurement of the proper motion of the PSR. The X-ray temperature of the ambient medium is ~700 eV corresponding to a sound speed of 350 to 450 km/s. Thus, the Mach number of the flow may be of order unity.

What is the nature of the ring and jet?

The interpretation of the nearly circular ring-like feature poses some difficulty. Its circularity implies either a (limb-brightened) isotropic PSR wind or, if the wind is equatorial, then a co-alignment of the jet (and probably therelative PSR velocity) with our line of sight. The ring may define the location of the TS or, in analogy to the Crab Nebula, a torus at a distance ~ 4R_{TS}. For subsonic incompressible flow and negligible B field strength, the apex of the nebula occurs at a distance R=R_{TS}(c/3V)$^{1/2}$, where c is the speed of light, and V is the relative velocity of the PSR with respect to the ambient medium (e.g., Kennel & Coroniti 1984). In our case, R~10″ (1 e-folding length upstream of the PSR) and, for a transonic (M~1) flow, V~500 km/s so R_{TS}~1″ or less. Thus, the ring is likely similar to the Crab torus and the TS is too close to the PSR to be easily resolved.

References

Bucciantini, N. 2002, A&A 387, 1066
Kennel, C.F., & Coroniti, F.V. 1984, ApJ 283, 694
Wilkin, F.P. 1996, ApJ, 459, L31