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 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° 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 the spectrum and the bright non-thermal nebula indicate a soft thermal X-ray emission surrounding the PWN and extends throughout the Chandra field of view. This soft emission is from the IC 443 SNR.

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° 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 toward 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 hyperbolic (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.

Synchrotron Cooling in the Tail

The PWN extends about 3.5' (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 $\tau_{\text{cool}}=100$ kyr.

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-rotation 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 ~4 R$_{\text{PSR}}$. For subsonic incompressible flow and negligible B field strength, the apex of the nebula occurs at a distance $R_{\text{PSR}}(\frac{3}{2})$, where $c$ is the speed of light and $\dot{V}$ is the relative velocity of the PSR with respect to the ambient medium (e.g., Kennel & Coroniti 1984). In our case, $R_{\text{PSR}}=10^4$ (1 e-folding length upstream of the PSR) and, for a transonic ($M=1$) flow, $V=500$ km/s at $\dot{V}=10^3$ 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

