A BOW SHOCK NEBULA AROUND A COMPACT X-RAY SOURCE IN THE SUPERNova REMNANT IC 443

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ABSTRACT

We present Chandra spectra and high-resolution images of the hard X-ray feature in the southern edge of the supernova remnant (SNR) IC 443 that reveal a comet-shaped nebula of hard emission that contains a softer point source at its apex. We also present 20, 6, and 3.5 cm Very Large Array maps that clearly show the cometary nebula. Based on the radio and X-ray morphology and spectrum, and the radio polarization properties, we argue that this object is a synchrotron nebula powered by the compact source that is physically associated with IC 443. The spectrum of the soft point source is adequately but not uniquely fitted by a blackbody model \( kT = 0.71 \pm 0.08 \text{ keV}, L = (6.5 \pm 0.9) \times 10^{31} \text{ ergs s}^{-1} \). The morphology of the nebula can be explained by the supersonic motion of the neutron star \( (V_{\text{NS}} = 250 \pm 50 \text{ km s}^{-1}) \), which causes the relativistic wind of the pulsar to terminate in a bow shock and trail behind as a synchrotron tail. This velocity is consistent with an age of \( 30,000 \) yr for the SNR and its associated neutron star.

Subject headings: ISM: individual (IC 443) — pulsars: individual (CXOU J061705.3+222127) — stars: neutron — supernova remnants

1. INTRODUCTION

The mixed-morphology Galactic supernova remnant (SNR) IC 443 \((l, b = 189^\circ 71, +3^\circ 50)\) has been the subject of extensive studies at all wavelength bands (Fesen 1984; Braun & Strom 1986; van Dishoeck, Jansen, & Phillips 1993; Asaoka & Aschenbach 1994) and is especially well known for its interaction with surrounding molecular clouds (Burton et al. 1990; Bocchino & Bykov 2000). With its large variety of shocked molecular species detected along its southeast edge, IC 443 has become a standard laboratory for studying shock chemistry (van Dishoeck et al. 1993 and references therein).

IC 443 is also of interest because it is coincident with the unidentified EGRET source 2EG J0618+2234 (Sturmer & Dermer 1995; Esposito et al. 1996) and thus has stimulated theoretical work aiming to explain the production of GeV \( \gamma \)-rays by shell SNRs (Sturmer, Dermer, & Mattox 1996; Sturmer et al. 1997; Gaissier, Prather, & Staeve 1998; Baring et al. 1999; Bykov et al. 2000).

In the X-ray band, Petre et al. (1988) found that the bulk of the emission was thermal \((T \sim 10^7 \text{ K})\), typical of middle-aged SNRs. However, Wang et al. (1992) found evidence with Ginga for a hard X-ray component extending up to 20 keV. Follow-up observations with ASCA revealed that much of this hard X-ray emission came from a single, unresolved feature at the southern edge of the radio shell (Keohane et al. 1997, hereafter K97). The hard X-ray feature (HXF) is positionally coincident with a region where the radio spectral index is considerably flatter than that of the SNR as a whole (i.e., \( \alpha < 0.24 \) vs. \( \alpha = 0.42 \), where \( F \propto v^{-\alpha} \); Green 1986; Kovalenko, Pynzar, & Udal"tsov 1994).

K97 favored a model in which synchrotron emission was being produced in a region of enhanced particle acceleration resulting from the SNR/molecular cloud interaction. Recent BeppoSAX data (Bocchino & Bykov 2000) also support the K97 interaction model. An equally viable model, favored by Chevalier (1999, hereafter C99), posits that the HXF is synchrotron emission powered by an energetic neutron star. To distinguish between these two competing hypotheses we have undertaken high-resolution X-ray and radio observations toward the HXF. These new Chandra and Very Large Array (VLA) observations strongly favor C99’s neutron star hypothesis.

2. OBSERVATIONS AND ANALYSIS

2.1. Chandra X-Ray Observatory

The Chandra X-Ray Observatory performed a short (10 ks) observation of IC 443 on 2000 April 10, during the first cycle of guest observations (AO-1). The HXF was centered on the I3 chip of the Advanced CCD Imaging Spectrometer (ACIS). We followed the standard CIAO procedures outlined in Version 1.3 of the CIAO Beginner’s Guide for CIAO Release 1.1, using the ACISID2000-01GAINN0001.FITS gain file to extract high-resolution images in both hard \((E > 2.1 \text{ keV})\) and soft \((E < 2.1 \text{ keV})\) spectral bands (Fig. 1).

The HXF is resolved by this Chandra observation as a nebular region of diffuse emission with a cometary tail (Fig. 1). Within the nebula there is an unresolved point source that we have designated as CXOU J061705.3+222127. The nebula of hard emission exhibits bow shock morphology with a width of \(~35^\circ\) and a minimum standoff distance of \( r_s \approx 8.5' \). The X-ray point source lies at the apex of the nebula, located at \((J2000) \alpha = 06^h 17^m 05^s 31, \delta = 22^\circ 21' 27'' 3\). It is especially visible in the soft \((E < 2.1 \text{ keV})\) X-ray band (Fig. 1).

To compare the X-ray luminosity of the cometary nebula with statistical studies of pulsar wind nebulae (PWNe; e.g., Seward & Wang 1988, see §3), we integrated the power-law model of K97 over the Einstein band \((0.2–4 \text{ keV})\)—thus deriving \( L_x \sim 5 \times 10^{38} \text{ ergs s}^{-1} \). The Chandra flux (over the same range) yields consistent results, albeit with larger uncertainties.

2.2. Very Large Array

All radio observations were made on 1997 August 26 and December 31 with the VLA in the C and D arrays, respectively.

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3 The VLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation.
A log of the observations is summarized in Table 1. The data acquisition and calibration were standard, using J0632+103 as a phase calibrator and 3C 138 as the flux density and polarization angle calibrator.

The cometary and bow shock morphologies of the extended source are even more pronounced at radio wavelengths, extending some 2° to the northeast of the soft X-ray source. Although we display only the 3.5 cm image and distribution of linearly polarized emission in Figure 2, similar structure is visible at 6 and 20 cm. The peak in the radio emission lies ∼6′′ to the northeast of the compact X-ray source, which has no counterpart in the radio images (>2 mJy). The direction of the \( E \)-vectors are generally parallel to the shock normal, as would be expected for evolved SNRs with circumferential magnetic fields. The character of the magnetic field evidently changes substantially in the area dominated by the X-ray emission, where the magnetic field direction appears to wrap around the “head” of the hard nebula, tracing a bow shock morphology. The average degree of polarization in this region is 8%. This is likely a lower limit since, owing to the compact size of the nebula, there is likely some beam depolarization occurring. To the northeast, where the field is more ordered, the percentage polarization is uncharacteristically strong for an evolved SNR, exceeding 25% in several locations.

The integrated flux density over the entire length of the cometary nebula is given for three frequencies in Table 1. An approximate value of 230 ± 200 mJy was also obtained from the 327 MHz image presented by Claussen et al. (1997). The increased error in estimating the flux density at low frequencies is due to the uncertainty in background subtraction. Within the errors, the radio spectrum is well represented by a flat spectral index \( \alpha_r = 0.0 \) and a mean flux density of 206 mJy. In contrast, K97 measured an X-ray spectral index of \( \alpha_x = 1.3 \pm 0.2 \), which implies a break in the spectrum near 4 \times 10^{13} \text{ Hz}. The radio luminosity of the cometary nebula, determined by integrating the spectrum from 10 MHz to 100 GHz, is \( L_R = 5.5 \times 10^{31} (d/1.5 \text{ kpc})^2 \text{ ergs s}^{-1} \), or less than 1% of \( L_X \) for IC 443 as a whole.

### Table 1: Summary of VLA Observations of the Cometary Nebula

| Frequency (GHz) | Time (minutes) | Beam (arcsec) | \( F_M \) (mJy) |
|----------------|----------------|---------------|----------------|
| 8.46 \ldots   | 13             | 8.6 \times 7.6 | 195 \pm 8      |
| 4.86 \ldots   | 36             | 5.0 \times 4.8 | 173 \pm 11     |
| 1.46 \ldots   | 53             | 15.5 \times 14.5 | 229 \pm 34    |

**Note.**—Col. (1): Observing frequency. Col. (2): Total time on source. Col. (3): Angular resolution. Col. (4): Integrated flux density of the cometary nebula.

2.3. Spectra

A spectrum of CXOU J061705.3+222127 was extracted from this short Chandra observation with the surrounding hard
nebula subtracted as background (i.e., an annulus with an inner and outer radius of 4'3 and 23'6, respectively). These spectra were binned by a factor of 256 (pulse-height analyzer channels), and the softest three ACIS-I channels were ignored. As discussed above, the point source is significantly softer than the surrounding hard nebula, implying a likely thermal origin for the emission. For this reason, we modeled the point source spectrum as blackbody radiation, although this fit was not statistically unique due to the small data set.

The best-fit ($\chi^2 < 1.1$) blackbody temperature and luminosity are $kT = 0.71 \pm 0.08$ keV and $L = (6.5 \pm 0.9) \times 10^{31}$ ergs s$^{-1}$ [i.e., $A = 0.025 \pm 0.003 (d/1.5$ kpc)$^2$ km$^2$, $F_{1-15\text{keV}} = 2 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$]. We assume K97's best-fit column density, $N_{\text{H}} = 1.3 \times 10^{22}$ cm$^{-2}$ (see Fig. 3).

3. DISCUSSION

The soft X-ray point source in IC 443 is one of a growing number of young neutron star candidates associated with SNRs (Helfand 1998), which have a diverse range of properties (Chakrabarty et al. 2001). The long period (8–10 s) and claimed high field (10$^{14}$–10$^{15}$ G) of anomalous X-ray pulsars (AXPs) and soft $\gamma$-ray repeaters (SGRs) differ from the canonical young radio pulsars with periods $P \approx 15$–500 ms and field strengths of $B \sim 10^{12}$–$10^{13}$ G. The radio-quiet neutron stars (RQNSs), with their thermal X-ray emission and lack of radio pulsations, may be altogether different from either of these two classes of objects (Pavlov et al. 2000).

In the absence of detectable pulsations, canonical radio pulsars can be distinguished from AXPs, SGRs, and RQNSs by the presence of an extended synchrotron nebula, powered by the energetic relativistic wind (Gaensler, Bock, & Stappers 2000a). We argue that the cometary nebula around the X-ray point source in IC 443 is most likely such a PWN. This nebula has all the expected observational characteristics (C99; Gaensler et al. 2000b): a flat spectrum radio emission ($\alpha_r = 0.1$–0.3), a steep X-ray spectrum ($\alpha_X = 1.0$–1.5), and a high degree of linear polarization ($>5\%$). Morphologically it closely resembles PWNe detected toward the SNRs W44 and G5.4–1.2 (Frail & Kulkarni 1991; Frail et al. 1996), both of which contain active pulsars. It has been argued (Frail & Kulkarni 1991; Frail et al. 1996) that these nebulae have developed bow shocks as a result of ram pressure confinement of the pulsar wind due to the high space velocity of their pulsar through the surrounding medium. We assert that the X-ray point source in IC 443 is a young pulsar that has traveled (ballistically) from its birthplace to its present location, near the edge of the decelerating SNR.

Accepting this hypothesis, we now infer the salient physical properties of the neutron star and corresponding PWN. The bounce point, the shock, and the codispersive point are (i.e., $c_s$) given by $V_{\text{SN}} = \beta V_{\text{NS}} = \beta r_{\text{SN}}$. Moreover, the shock velocity of the SNR can be similarly expressed as $V_{\text{SN}} = c_s r_{\text{SN}}$, where $c_s = \frac{\dot{E}}{\rho V_{\text{SN}}^2}$ for a Sedov SNR. Here we adopt $c_s = 3/10$ (C99). Combining $V_{\text{SN}}$ and $V_s$, and assuming $V_s = 100$ km s$^{-1}$ (C99), gives $V_{\text{SN}} = V_s/c_0 = 225$–300 km s$^{-1}$, a result that is independent of distance and only weakly dependent on the evolutionary state of the SNR (i.e., $c_0$).

We note that the tail of the hard nebula does not point toward the geometric center of the SNR. However, the blast center and geometric center of an SNR can be quite different in the presence of large-scale density gradients (Dohm-Palmer & Jones 1996; Hnatyk & Petruk 1999). Such a density gradient, combined with a cross-wind, could possibly account for the apparent discrepancy.

We are able to make a second approximation of $V_{\text{SN}}$ with respect to the local medium by means of the nebula’s bow shock morphology. K97 fitted the SNR with an X-ray temperature $kT \approx 1$ keV, implying a sound speed $c_{\text{sound}} \approx 100$ km s$^{-1}$.

The energy source for the synchrotron nebula must ultimately be derived from the particles and field generated by the compact central neutron star and therefore some fraction of the spin-down power $E$ is powering this emission. Empirical relations have been derived for known PWNe between $E$ and the observed X-ray and radio luminosities ($L_X$ and $L_{\text{radio}}$) that enable us to estimate the current rotation period $P$ and the dipolar surface field $B$ of the compact object.

For the value of $L_X$ derived in $\S$ 2, we obtain $E \sim 2 \times 10^{36}$ ergs s$^{-1}$ (Seward & Wang 1988). Frail & Scharrington (1997) and Gaensler et al. (2000b) note that $E \approx 10^{36}$ ergs s$^{-1}$ for known radio PWNe, which yields a value of $E \sim 6 \times 10^{36}$ ergs s$^{-1}$, so in the discussion that follows we adopt $E = 10^{36}$ ergs s$^{-1}$ (i.e., $E_{\text{SNR}} = 1$). Equating the pressure of the wind $\rho V^2_{\text{SN}}$, to the ram pressure due to the neutron star’s motion through the surrounding gas $\rho V_{\text{NS}}^2$, we derive a density of $<0.1$ cm$^{-3}$ for our adopted values of $E$ and $V_{\text{SN}}$. This density is typical of that expected for the hot X-ray interior of the SNR and is orders of magnitude below that expected in the dense molecular ring against which the neutron star and its nebula are projected (see van Dishoeck et al. 1993).

The spin-down luminosity of a pulsar is related to $P$ and $B$ by $E \propto B^2 P^{-3}$, while the characteristic age of the pulsar is expressed as $\tau \propto B^{-3} P^2$. It is straightforward to show that for
a pulsar born spinning rapidly (i.e., $P_s \ll P$), which loses energy predominately via magnetic dipole radiation, $P = 145\, \text{ms} (r_1 E_1)^{-1/2}$ and $B = 3.3 \times 10^{15}\, \text{G} (r_2 P_1)^{15}$. Thus, with our nominal choice of parameters, the period and magnetic field closely match those of other young pulsars (e.g., PSR B1757–24; Frail & Kulkarni 1991).

It is worth reexamining the nature of the unidentified EGRET source 2EG J0618+2234 (Sturmer & Dermer 1995; Esposito et al. 1996). Nel et al. (1996) note that all known $\gamma$-ray pulsars have a large ($>0.5$) ratio of $E_{\gamma}/dE_{\gamma}$. For $d \sim 1.5$ kpc and our derived $E \sim 10^{48}\, \text{ergs}^{-1}$, this ratio is over 400, similar to that of the $\gamma$-ray–emitting PSR B1706–44, suggesting that the unidentified EGRET emission originates from the neutron star or the PWN. The difficulty with this interpretation is that our proposed neutron star and PWN lie several arcminutes outside the statistical 99% error radius of the EGRET source (Sturmer et al. 2001). However, the positions of EGRET sources in the Galactic plane are subject to systematic error (e.g., Hunter et al. 1997), and contamination from other nearby $\gamma$-ray sources may be confusing this result. A future observation with the International Gamma-Ray Astrophysics Laboratory should be able to resolve this issue.

4. CONCLUSION

In summary, the hard X-ray feature in IC 443 is best interpreted as a wind nebula powered by a young neutron star. The PWN interpretation is suggested first on morphological grounds by the Chandra and VLA images, which show a comet-shaped nebula with a soft X-ray point source at its apex. The measurement of significant polarization and a flat radio spectrum further strengthens the argument that this is synchrotron emission from a PWN. The X-ray spectrum of the point source is adequately, but not uniquely, fitted by a blackbody model, suggesting that the emission is thermal in origin. The inferred physical properties of the nebula and point source (i.e., $\tau$, $V_{\text{ms}}$, $E$, $P$, $B$) support our hypothesis that IC 443 and the pulsar were produced approximately 30,000 yr ago in a core collapse supernova event.

Despite the evidence in favor of a real physical association between IC 443 and the compact source within the cometary nebula, there are a few puzzles that remain to be explained. As mentioned previously, one might expect the “tail” of the cometary nebula to point back to the origin of the SNR and the pulsar. Given the complex kinematics and distribution of the gas in IC 443 (Giovanelli & Haynes 1979; van Dishoeck et al. 1993), the blast center is probably not the geometric center. We also note that the object could possibly be correlated with the faint radio source G189.6+3.3 (Asaoka & Aschenbach 1994). A final problem concerns the apparent absence of X-ray and radio pulsations from the IC 443 point source (Kaspi et al. 1996; K97). A recent Arecibo observation (B. A. Jacoby, S. B. Anderson, D. A. Frail, and J. W. Keohane 2001, in preparation) has also failed to detect periodicity toward the source.

In our view, these null results present no immediate problem for our young neutron star hypothesis since pulsed X-rays from Vela-like pulsars have proven difficult to detect due to their soft spectra and contamination from the surrounding nebular emission (e.g., Becker & Trümper 1997). Furthermore, it is entirely possible that the radio beam may not intersect our line of sight (Lorimer, Lyne, & Camilo 1998).

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