NON-THERMAL X-RAY AND RADIO EMISSION FROM THE SNR N 157B

John R. Dickel¹, and Shiya Wang¹

¹Astronomy Department, University of Illinois at Urbana-Champaign, 1002 West Green Street, Urbana IL 61801, USA

ABSTRACT

The supernova remnant N 157B contains a pulsar and three distinct synchrotron components with rather unusual properties. 1) A somewhat irregular elliptical pulsar wind nebula (PWN) visible in both X-ray and radio wavelengths. The nebula is quite symmetrical with an extent of about 10 × 5 parsecs but offset along the long axis by about 4 pc from the pulsar position. It is apparently the result of a short-lived injection of energetic particles, perhaps starting at the time of explosion. 2) A very bright X-ray shock region located just outside the pulsar position in the edge of the PWN. This is undetected in the radio. We attribute this to a new burst of particles from the pulsar suggesting there are multiple episodes rather than continuous injection. 3) The beginning of a radio synchrotron shell on the southern side of the SNR where thermal X-rays appear to arise suggesting that N 157B is starting to become a composite SNR.

INTRODUCTION

N 157B (Henize, 1956) is a Crab-type supernova remnant (SNR) just 7 arcmin from the center of 30 Doradus (Bode, 1801) in the Large Magellanic Cloud (LMC). It contains a 16-ms X-ray pulsar undetected at any other wavelength (Marshall et al. 1998). There is bright non-thermal X-ray emission with structure on arcsec scales just around the pulsar with an extended feature off to the northwest (Wang and Gotthelf, 1998a, 1998b; Wang et al. 2001). There is bright non-thermal radio emission from the extended feature but not at the pulsar location (Lazendic et al. 2000). We shall call the extended emission region the pulsar wind nebula (PWN). The overall structure suggests that the pulsar is moving toward the southeast. There is also extended radio emission toward the south that gives a hint of a shell, suggesting that the remnant may be in transition to becoming a composite remnant with a shell and a pulsar wind nebula.

The differences in the radio and X-ray structures plus the apparent large motion of the pulsar make this SNR unusual. We shall describe its properties and then discuss the implications of the data.

X-RAY – RADIO COMPARISONS

Morphology

Figures 1 and 2 show the similarities of the radio and X-ray emission of the PWN component of N 157B but a striking difference toward the pulsar. The radio emission in the pulsar wind component sits on a plateau of the rest of the remnant. Fine structure in the PWN appears very similar in both wavelength ranges although the radio emission extends further northwest. This structure probably represents clumpiness in the interstellar medium or in pre-explosion mass loss of the progenitor.

The peak in the X-ray emission in the compact source around the pulsar is 13 times the brightness of the peak in the PWN but in the radio there is nothing seen above the residual brightness of the PWN. The pulsar lies at $05^h37^m47.2^s$ and $−70°10′23″$ (Wang and Gotthelf, 1988b) about 16″ out from the center along the SE axis of the tail. The pulsar is about 1″ closer to the center of the tail than the peak of the X-ray emission.
Fig. 1. Chandra X-ray image of the pulsar wind part of the supernova remnant N 157B smoothed to a resolution of 1.8 arcsec. The contours are 5, 10, 20, 30, 40, 100, 300, and 600 counts over the 0.1 – 10 kev range of the HRC detector. The thin line shows the location of slices shown in Figure 3.

Fig. 2. ATCA 6-cm radio image of the pulsar wind part of the supernova remnant N 157B at a resolution of 1.8 arcsec. The contours are 2, 3, 4, 6, and 7 mJy beam$^{-1}$. The thin line shows the location of slices shown in Figure 3 and the cross is the position of the pulsar.
Fig. 3. X-ray and radio slices from southeast to northwest through the pulsar position and along the major axis of the elliptical PWN of N 157B as shown in Figures 1 and 2. The slices are averaged over a width of 15″. The radio units are Jy beam$^{-1}$ and the X-ray ones are counts psf$^{-1}$ normalized to fit on the same scale.

Fig. 4. Slices from northeast to southwest perpendicular to the major axis shown in Figures 1 and 2. The ones through the center of the PWN are 18″ wide centered on the radio peak and the ones through the pulsar position are 5″ wide.
Further details of the emission are revealed by the slices presented in Figures 3 and 4. The emission from the PWN is clearly more extended in all directions at radio wavelengths than at X-ray ones. The overall symmetry is the same, however, with an approximately elliptical shape centered about a point at $05^h37^m45.5^s$ and $-69^\circ10'09''$. The radio emission falls off uniformly out to a semi-major axis of $20''$ in the SE-NW direction and $10''$ in the NE-SW direction.

There is no sign of the pulsar or any enhancement in the radio emission, $< 0.1$ mJy beam$^{-1}$, at the pulsar’s position of $05^h37^m47.2^s$ and $-70^\circ10'23''$ (Wang and Gotthelf, 1988b). The non-thermal X-rays around the pulsar position, on the other hand, show a strong approximately elliptical component, about $7'' 	imes 3''$ with its long axis perpendicular to the long axis of the PWN tail. Wang and Gotthelf (1998) suggested that this small source could be a bow-shock from the particles leaving the moving pulsar. We shall henceforth call that structure the shock region. From the inner (NW) edge of this shock, the X-ray emission first decreases somewhat and then increases gradually toward the radio center of the PWN but peaks $3''$ before the radio and then falls sharply toward the northwest.

**Spectra**

To compare the actual brightnesses of the features, we show their spectra in Figure 5. The squares represent the integrated values for the radio emission of the entire SNR. They give a spectral index, $\alpha$, of $-0.19 \pm 0.1$, where the flux density $S_\nu \propto \nu^{-\alpha}$ (Lazendic et al. 2000). XMM-Newton spectra, that cannot resolve angular detail, show that most of the X-ray emission from the SNR has a steep power-law spectrum with $\alpha = -1.83 \pm 0.03$ although some thermal emission is present as well (Dennerl et al. 2001). They do not give a value for the actual X-ray flux.

For the PWN, the lower frequency radio data do not have sufficient resolution for a good separation of the components so we report only the 4.8- and 8.6-GHz results (Lazendic et al. 2001). The spectral index for the PWN is more uncertain because of the SNR background. The value of $\alpha = -0.1 \pm 0.2$ could easily be the same as that of the whole SNR. The error of the spectral index for this fit to only the two data points tries to take into account the uncertainty in evaluation of the background. We cannot determine the radio spectrum of the shock region because it is not detected. We do show the upper limits for its flux density at the two radio frequencies.

The x-ray spectra are from the paper by Wang and Gotthelf (1998b). Their formal fits give values of $\alpha = -1.5 (\pm 0.2, -0.3)$ for the PWN and $\alpha = -1.9 \pm 0.2$ for the bow-shock. Realizing that these errors are only for the formal fits to the data, we suggest that the slopes of both components could be the same but that of the PWN cannot be much steeper than that of the shock region.

**DISCUSSION**

For analysis, we divide the SNR into three parts as outlined by Wang and Gotthelf (1998a) and discussed above: the elliptical pulsar wind nebula extending northwest from the pulsar with major and minor axes of $10 \times 5$ pc; the bright shock region ($\sim 2 \times 1/2$ pc) centered just outside the pulsar; and the entire SNR, about $30 \times 18$ pc across, which extends well beyond the images in Figures 1 and 2.

Assuming that the pulsar has been moving southeastward from an explosion site at the radio peak, we can estimate its speed using the characteristic spin-down age of 5000 years (Marshall et al. 1998; Wang and Gotthelf, 1998b). To have moved 4 pc, the pulsar has a speed of 800 km sec$^{-1}$, large but not impossible for a pulsar (Arzoumanian et al. 2002)). Because the PWN emission falls off in all directions from its center, including toward the pulsar, we are led to the conclusion that there was a brief period of particle injection by the pulsar, lasting up to about 1000 years after the explosion occurred. That period would account for the $\sim 3/4$ pc shift of the X-ray peak from the radio one and also allow for the apparent aging of the electrons on the outer edge of the PWN relative to the center. As higher energy electrons decay more rapidly from their synchrotron emission, those further from the pulsar should be the oldest and thus have reduced X-ray emission relative to the radio and steeper spectra (Pacini and Salvati, 1973; Reynolds and Chevalier, 1984). The particle injection and/or stimulation cannot have lasted much longer, however, or the emission in the PWN would still be bright toward the southeast between the PWN peak and the current location of the pulsar.

The emission from the shock region just around the pulsar appears to have arisen from a second injection of particles. The X-ray brightness rises so drastically just there and appears to sit on top of the decreasing PWN emission in that direction. The radio emission is below detection level. We also note that if the injection of particles has been continuous, the X-ray spectrum of the region closest to the pulsar should be flatter (harder) than that of the region further from the current pulsar position, but that is not the case. Thus the newer particles around the pulsar must have been injected with a different spectrum or be interacting with a very different medium that those injected earlier.
Fig. 5. Full spectrum of the SNR N157B. The open boxes are for the entire SNR; the crosses are for the pulsar wind nebula; and the open circle and upper-limit arrows are for the shock region.

near the center of the overall PWN. Finally, the center of this shock source is slightly (about 1/4 pc) outside the pulsar position. These conditions lead us to believe that the object is indeed a shock region caused by the supersonic motion of the particles coming from the pulsar moving at about 800 km sec$^{-1}$ plus their injection speed and perhaps interacting with a reverse shock from the initial blast wave. Without a more accurate separation of the thermal component of the X-ray emission in that region to evaluate the temperature and density of the gas, we cannot determine the actual sound speed but the relative motion could be enough to generate a strong shock wave and compressed magnetic fields across which to accelerate particles to even greater energies than they get from the pulsar. The pulsar may have also encountered a density enhancement which will further increase the total emission to produce the high observed X-ray brightness. Indications of a clumpy medium around N 157B include many H$\alpha$ filaments and a very low polarization of the radio emission, presumably caused by significant Faraday rotation (Lazendic et al. 2000). The other lumps in the PWN may represent temporary increases due to previous brief episodes of acceleration near density enhancements.

We don’t know the radio spectral index of the shock region so we don’t know if the energy injection in that spectral range is the same for both episodes. To get an approximate ratio of radio to X-ray luminosities, we will assume that the radio spectrum of the shock region is the same as the rest of the SNR, $\sim -0.2$. Extrapolation of any value steeper than about $-0.3$ would require less X-ray emission than observed. With the adopted spectral index, we calculate an upper limit to the radio luminosity between $10^7$ and $10^{11}$ Hz of $\sim 4 \times 10^{32}$ erg sec$^{-1}$ or about 1/2000 of the X-ray luminosity in the 0.2 – 4 keV band (Wang et al. 2001). This upper limit is a low ratio for either a pulsar wind alone, e.g. 0540-693 has a ratio of radio to X-ray luminosity of 1/120, or for an SNR with shock generated X-ray emission, e.g. AD1006 has a ratio of about 1/100 (taken from Allen et al. 2001). Perhaps the combined processes may create a harder spectrum at low energies but then a sharper break at the transition between the emission in the two frequency ranges.

While still qualitative, this description of multiple episodes of particle injection from the pulsar is the only one we can come up with to explain all the data. Better radio resolution and sensitivity plus improved spectra in all
wavelength bands, including a detection of infrared and optical continuum emission, will be important for checking these ideas.

ACKNOWLEDGEMENTS

We thank Paul Plucinsky, Steve Reynolds, Brian Fields, You-Hua Chu, Douglas Bock, Martin Guerrero, and Pat Slane for help and ideas. This research is supported by NASA grant NAG 5-11159.

REFERENCES

Allen, G., R. Petre, and E. Gotthelf, X-ray synchrotron emission from 10 – 100 Tev cosmic-ray electrons in the supernova remnant SN 1006, Astrophys. J., 558, 739-752, 2001.
Arzoumanian, Z., D. Chernoff, and J. Cordes, The velocity distribution of isolated radio pulsars, Astrophys. J., 568, 289-301, 2002.
Bode, J. Algemeine beschreibung und nachweisung der gestirne (Berlin: Beym Verfasser), 90, 1801.
Dennerl, K., F. Haberl, B. Aschenbach, et al., The first broad-band X-ray images and spectra of the 30 Doradus region in the LMC, Astron. Astrophys., 365, L202-L207, 2001.
Gotthelf, E. and Q. D. Wang, A spatially resolved plerionic X-ray nebula around PSR 0540-69, Astrophys. J., 532, L117-L120, 2000.
Lazendic, J., J. Dickel, R. Haynes, P. Jones, and G. White, Radio properties of the supernova remnant N157B, Astrophys. J., 540, 808-813, 2000.
Marshall, F., E. Gotthelf, W. Zhang, J. Middleditch, and Q. D. Wang, Discovery of an ultrafast X-ray pulsar in the supernova remnant N157B, Astrophys. J., 499, L179-L182, 1998.
Pacini, F. and M. Salvati, On the evolution of supernova remnants. I. Evolution of the magnetic field, particles, content, and luminosity, Astrophys. J., 186, 249-266, 1973.
Reynolds, S. and R. Chevalier, Evolution of pulsar-driven supernova remnants, Astrophys. J., 278, 630-648, 1984.
Reynolds, S. and H. Aller, Radio observations of the Crab-like supernova remnant 3C 58. I. Total intensity observations, Astrophys. J., 327, 845-852, 1988.
Wang, Q. D. and E. Gotthelf, ROSAT and ASCA observations of the Crab-like supernova remnant N157B in the Large Magellanic Cloud, Astrophys. J., 494, 623-635, 1998a.
Wang, Q. D. and E. Gotthelf, ROSAT HRI detection of the 16 ms pulsar J0537–6910 inside supernova remnant N157B, Astrophys. J., 509, L109-L112, 1998b.
Wang, Q. D, E. Gotthelf, Y.-H. Chu, and J. Dickel, Detection of an X-ray pulsar wind nebula and tail in SNR N157B, Astrophys. J., 559, 275-281, 2001.

johnd@astro.uiuc.edu, swang9@astro.uiuc.edu