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Peculiar Differences in Radio and X-ray Synchrotron Radiation from Pulsar Wind Nebulae

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Abstract. Several Crab-type supernova remnants appear to have very bright non-thermal X-ray cores just around the pulsar or expected pulsar. This X-ray brightness is often not matched by a corresponding increase in radio emission. The best example of this phenomenon is in N157B in the LMC. G21.5–0.9 and possibly 3C 58 also show it while the Crab Nebula and 0540–69.3 do not. Some method to enhance the higher energy particles must be present in these objects.

1. Introduction

Young supernova remnants (SNRs) containing pulsars show a central brightening with increased X-ray and radio emission in the form of a pulsar wind nebula (PWN). Both the radio and X-ray emission have power-law spectra characteristic of synchrotron radiation. In general the overall extent of the radio emission is somewhat larger than that of the X-ray emission because the particles furthest from the pulsar have been ageing longer and the higher-energy X-ray producing particles have radiated away their energy faster.

In some PWNe, there is a very bright core seen in X-rays just around the pulsar without any corresponding increase in radio emission. Table 1 lists the X-ray-to-radio luminosity ratios for several PWNe. We have adopted the standard radio frequency range of 10^7–10^{11} Hz and for the X-ray we choose the traditional 0.2–2.4 keV. Clearly the cores have relatively higher X-ray luminosities than do the Crab Nebula and 0540–69.3, both of which are known to be currently actively stimulating their nebulae.

2. N157B

N157B (Henize 1956) contains a 16 ms pulsar located at the peak of the X-ray contours in Figure 1, at $05^{h}37^{m}47\overset{s}{.}2$ and $-69°10'23''$ (Marshall et al. 1998). The line from northwest to southeast is an approximate major axis to the elliptical outline of the PWN. The peak of the X-ray brightness at the pulsar position is over 12 times its brightness at the peak to the northwest where the radio emission is the brightest. Except for the very bright X-ray feature with a size of about $7'' \times 3''$ around the pulsar, the two images are very similar although the extent of the X-ray ellipse along both axes is smaller than the radio one.

Table 1. Approximate X-ray-to-radio luminosity ratios for PWNe.

SNR name	L_X/L_R	References
N157B		Lazendic et al. (2000); Wang et al. (2001)
Eliptical PWN	15	
Pulsar core	> 2150	
G21.5–0.9		Bock et al. (2001); Slane et al. (2000)
Elliptical PWN	12	
Core	> 330	
3C 58		Bietenholz et al. (2001); Slane et al. (2002)
Whole SNR	1.0	
Core	> 1400	
Crab	14	Lozinskaya (1992)
0540–69.3 (PWN)	12	Dickel et al. (2002); Gotthelf & Wang (2000)

The morphology suggests that the radio peak is the location of the explosion and that the pulsar has moved to the southeast at about 800 km s^{-1} during the 5000 year spin-down age of the pulsar (Marshall et al. 1998). The general decrease away from the radio peak and the smaller extent of the X-ray emission would argue that the particles furthest from the injection point at the time of the explosion have aged the most and radiated away the most energy. The extra bright X-ray emission around the pulsar with no radio counterpart remains a puzzle, however. There is a definite decrease in the X-ray emission between the two peaks so either the pulsar injection or the environment around the pulsar must have changed at some time.

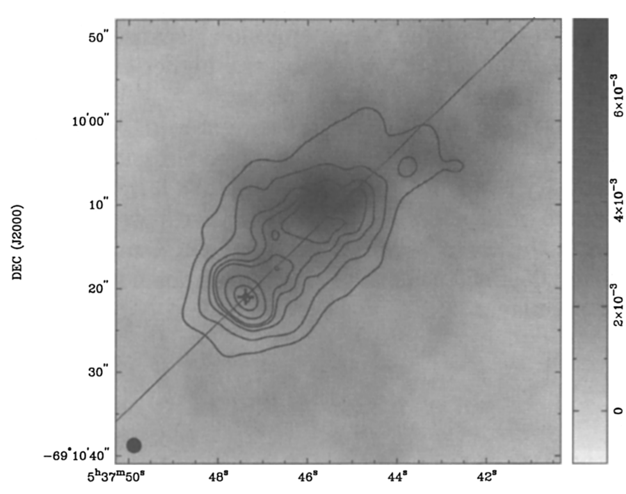

Figure 1. Radio image and X-ray contours of N157B, at a resolution of 1.″8 shown in the lower left corner. The contours are at 5, 10, 20, 30, 40, 100, 300, and 600 counts per point spread function (PSF). The line is the major axis of the elliptical pulsar wind nebula and the cross marks the pulsar position.

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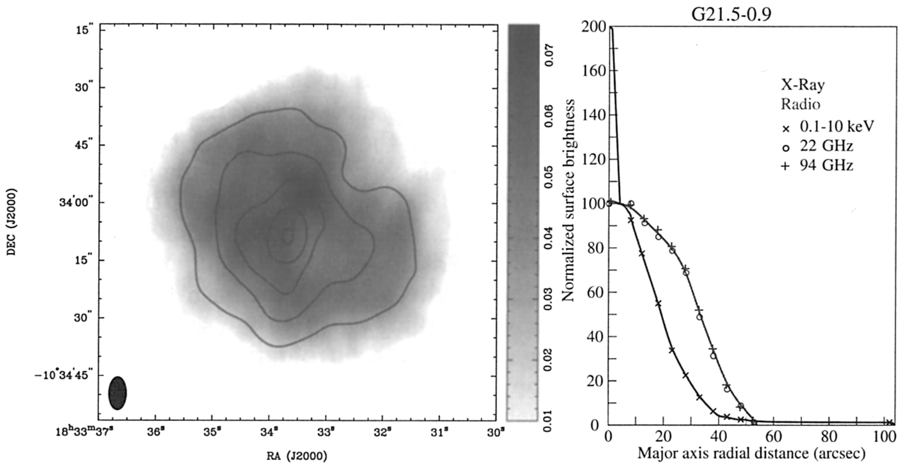

Figure 2. *Left panel:* Radio image and X-ray contours of G21.5–0.9 with a resolution of 7″ × 4″. The contours are at 20, 50, 100, 200, and 500 normalized counts PSF^{-1}. *Right panel:* Mean radial surface brightness determined by fitting elliptical rings to the emission as described in the text.

3. G21.5–0.9

The radio image and X-ray contours of G21.5–0.9 are shown in Figure 2 (left panel). The radio emission shows a reasonably symmetrical filled elliptical shape whereas the X-ray emission shows two additional components — a very bright core and a very faint extended outer component. For analysis and display, we have convolved the X-ray image to the 7″ × 4″ resolution of the radio one but the full resolution *Chandra* image shows that the core is extended with a half-power width of about 3″ (Slane et al. 2000). The X-ray emission has a power-law spectrum although the index appears to soften with increasing distance from the center (Warwick et al. 2001; Slane et al. 2000).

Determination of the radial variation in the emission was done by fitting elliptical rings to the brightness distribution with an axial ratio of 7 to 5 at a position angle of 45° for the major axis. The thickness of each ring is 5″ and the average brightness is plotted in Figure 2 (right panel). Note that even after convolution, the peak of the X-ray emission is twice the mean just around the core whereas the fluctuations in the radio emission in the central area are less than 10%. In addition, the X-ray emission in the overall ellipse falls off faster with radial distance than does the radio emission.

The more rapid fall off in X-ray brightness and the steepening of the spectrum with radius can be ascribed to the ageing effect of the particles in the outer part of the PWN. This phenomenon, however, does not explain the sudden sharp boundary of the X-ray core rather than the continued gradual increase in brightness toward the center. Could G21.5–0.9 be similar to N157B but with the pulsar motion directed toward us or not moving relative to the SNR but re-energizing the surroundings?

4. Discussion

The upper limit to the radio surface brightness just around the pulsar in N157B is less than 1/100 that toward the radio peak so the pulsar input must have dropped by that factor since the time of the explosion. If the production of particles from the pulsar responsible for the X-ray emission from its surroundings has dropped by the same factor, then the X-ray brightness of the PWN at the location of the initial stimulation must have declined from radiative or expansion losses by a factor of over 1200 in the 5000 years since the supernova.

Alternatively, the surrounding medium may have been altered. Van der Swaluw (these proceedings) has shown that, on this time scale, both a reverse shock from the interface of the ejecta with the surrounding medium plus the forward and reverse shocks from the boundary of the pulsar wind can significantly alter the structure within the nebula and around the pulsar. A significant increase in density around the pulsar can make the spectrum of the most energetic injected particles become harder (Reynolds & Chevalier 1984). This conclusion is qualitative at the current time and needs to be investigated quantitatively.

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