DISCOVERY OF A NEW PULSAR WIND NEBULA IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present new high-resolution radio and X-ray observations of the supernova remnant (SNR) B0453−685 in the Large Magellanic Cloud, carried out with the Australia Telescope Compact Array and the Chandra X-Ray Observatory, respectively. Embedded in the SNR shell is a compact central nebula producing both flat-spectrum polarized radio emission and nonthermal X-rays; we identify this source as a pulsar wind nebula (PWN) powered by an unseen central neutron star. We present a new approach by which the properties of a SNR and PWN can be used to infer upper limits on the initial spin period and surface magnetic field of the unseen pulsar, and we conclude that this star was an initial rapid rotator with current properties similar to those of the Vela pulsar. As is the case for other similarly aged sources, there is currently an interaction taking place between the PWN and the SNR’s reverse shock.

Subject headings: ISM: individual (B0453−685) — Magellanic Clouds — radio continuum: ISM — stars: neutron — supernova remnants — X-rays: ISM

1. INTRODUCTION

The Magellanic Clouds are ideal regions for studying supernova remnants (SNRs), the known distance and low extinction obviating many of the frustrations associated with studying Galactic SNRs. While this has proved useful in studying the shell emission produced by the interaction of SNRs with the ambient medium, just two Magellanic SNRs, B0540−693 (Manchester, Staveley-Smith, & Kesteven 1993) and N157B (Wang et al. 2001), are known to harbor a young energetic pulsar and its surrounding pulsar wind nebula (PWN). The lack of other PWNe in the Magellanic Clouds is likely due to a lack of spatial resolution—such resolution is only now being applied to Magellanic SNRs in both the radio and X-ray bands, and so the prospects are good for identifying new “composite” SNRs, containing both outer shells and central PWNe. Such sources are of particular interest, as the shell and PWN together provide unique constraints on the properties of the system.

We here present data that demonstrate that B0453−685 in the LMC is a composite SNR. This Letter primarily discusses the central PWN; interpretation of the surrounding shell will be the focus of a subsequent paper (S. P. Hendrick et al. 2003, in preparation).

2. OBSERVATIONS AND RESULTS

Radio observations of B0453−685 were carried out with the Australia Telescope Compact Array (ATCA). Observations were made simultaneously at 1.4 and 2.4 GHz with a bandwidth of 128 MHz at each frequency, using the 1.5G3 and 6.0C configurations on 2002 July 23 and August 26, respectively. A 38.6 ks X-ray observation of the same field was carried out using the ACIS-S3 detector of the Chandra X-Ray Observatory on 2001 December 18.

For each radio observation, the time on source was ∼11 hr. Antenna gains and polarization leakages were calibrated using observations of PKS B0252−712, while the flux density scale was tied to PKS B1934−638. The radio data were edited, calibrated, and imaged using standard techniques;4 the resulting resolution at each frequency is listed in Table 1.5 Analysis of the Chandra data will be reported elsewhere (S. P. Hendrick et al. 2003, in preparation).

2.1. Imaging and Polarimetry

Radio and X-ray images of SNR B0453−685 are shown in Figure 1. At radio frequencies, the source is clearly resolved into two components: a bright central core, embedded in an approximately circular limb-brightened shell. Table 1 lists the flux densities of these two components at 1.4 and 2.4 GHz after applying a correction for the local background. Fitting an ellipse to the perimeter of the shell component, we find that if one excludes the bright protrusion to the southwest, the shell can be fitted by a circle of diameter 120′′ ± 4′′, centered at R.A. = 04h53m37s, decl. = −68d29′30″ (J2000) (with an uncertainty ±2″). For a distance 50d0 kpc, the diameter of the shell is (29 ± 1)d0 pc.

Figure 2 shows that the central radio core is elongated along a position angle ∼45°, with dimensions 30″ × 20″ (i.e., a spatial size 7.3d0 pc × 4.8d0 pc). The core is brightest in the northeast, where it is dominated by a slightly extended region, with peak position R.A. = 04h53m38s.6, decl. = −68d29′21″ (J2000) (±0.5 in each coordinate). The core shows significant linear polarization, of mean fractional intensity 6% at 1.4 GHz and 8% at 2.4 GHz, as shown in Figure 2. The brightest region of the core is offset from the center of the shell by 11′′ ± 2′′. To the southwest, the surface brightness of the core fades with increasing distance from the peak.

The third panel of Figure 1 demonstrates that the morphology of B0453−685 in the soft X-ray band shows a broadly similar structure to that seen in the radio, again revealing a central core within a limb-brightened shell. In the hard X-ray band (Fig. 1, rightmost panel), only the central core is visible. The extent of this region is 14′′ × 7′′ (3.4d0 pc × 1.7d0 pc), less than half that seen in the radio. Figure 2 demonstrates that the

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3 1.5G is a nonstandard ATCA configuration and has successive spacings between the six antennas of 30.6, 535.7, 306.1, 413.3, and 3015.3 m.
4 See http://www.anf.csiro.au/computing/software/miriad.
5 The 1.4 GHz image was formed using all antennas, while the 2.4 GHz image excluded the sixth antenna so as to not overresolve the source.
positions of the peak emission in the X-ray and radio cores coincide to within the resolution of the observations.

2.2. Spectral Analysis

We have carried out a spectral index study of the radio data by smoothing the 1.4 and 2.4 GHz images to a common resolution of 15″ and then applying spectral tomography to these maps (Katz-Stone & Rudnick 1997). We find that the central core has a flatter radio spectrum than the surrounding shell: tomography implies for the core and core has a flatter radio spectrum than the surrounding shell: maps (Katz-Stone & Rudnick 1997). We find that the central evolution, while the central core is well fitted by the shell component is well fitted by the fitting to the resulting spectra, as will be described in detail by S. P. Hendrick et al. (2003, in preparation). To briefly summarize their results, the shell component is well fitted by the absorbed thermal spectrum expected in the Sedov phase of SNR evolution, while the central core is best fitted by an absorbed powerlaw. The best-fit parameters for the core are a foreground absorbing column \( N_H = (1.3 \pm 0.2) \times 10^{21} \text{ cm}^{-2} \), a spectral index \( \alpha = -0.9 \pm 0.4 \), and an unabsorbed flux density at 1 keV of \( f_\alpha = (6 \pm 1) \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \) (uncertainties quoted at 90% confidence). The corresponding X-ray luminosity over the energy range 0.5–10 keV is \( L_X \approx 6d_X^2 \times 10^{34} \text{ ergs s}^{-1} \). The spectral fits for the surrounding shell imply an age \( t \approx 13 \text{ kyr} \), a swept-up mass \( M_{sw} \approx 280 M_\odot \), an upstream density \( n_0 \approx 0.4 \text{ cm}^{-3} \), and an initial explosion energy \( E_0 \approx 5 \times 10^{50} \text{ ergs} \) (S. P. Hendrick et al. 2003, in preparation).

\( ^6 \) Bremsstrahlung (\( kT \approx 4 \text{ keV} \)) can also fit the central core, but the absence of lines demands either absurdly low abundances or an extremely underionized plasma (ionization timescale \( n_0 t < 100 \text{ yr cm}^{-3} \)).

### Table 1

| Waveband (cm) | Resolution (arcsec) | Flux Density (mJy) |
|---------------|---------------------|--------------------|
| 1.4 GHz       | 7.3 × 6.7           | Core: 46 ± 2, Shell: 140 ± 2, Total: 186 ± 3 |
| 2.4 GHz       | 9.2 × 8.4           | Core: 46 ± 2, Shell: 105 ± 2, Total: 151 ± 3 |

3. Discussion

The core embedded in B0453–685 is centrally located, polarized, has a filled-center morphology and a flat radio spectrum, and is coincident with a smaller nonthermal X-ray nebula. These properties demonstrate that B0453–685 is a composite SNR, containing a synchrotron-emitting PWN powered by a neutron star embedded in a shell SNR.

3.1. Properties of the Central Pulsar

Within the core, no radio or X-ray point source corresponding to the central pulsar is apparent. We can calculate upper limits on the flux from such a source as follows. At radio wavelengths, we made images of the field using only the longest (>3000 m) five baselines in each configuration. At both 1.4 and 2.4 GHz, the brightest region of the core was still detected

![Fig. 1.—Radio and X-ray images of SNR B0453–685. The left two panels show ATCA radio images of the source at 1.4 and 2.4 GHz, while the right two panels show Chandra X-ray images of B0453–685 in the soft and hard bands. The two radio images have both been smoothed to a resolution of 10″ × 10″. The sensitivity of the radio images are 95 and 65 \( \mu \text{Jy beam}^{-1} \) at 1.4 and 2.4 GHz, respectively. Both radio images are shown over the same gray-scale range, −0.4 to +5.7 mJy beam\(^{-1}\). The X-ray images have both been smoothed with a Gaussian of FWHM 5″ × 5″; the gray-scale ranges are 0%–100% and 0%–56% of the peak for the soft- and hard-band images, respectively. In all four panels, the point-spread function is shown by the ellipse in the lower right corner, and the gray scale is shown using a linear transfer function.]

![Fig. 2.—Radio and X-ray images of the core of SNR B0453–685. The gray scale shows X-ray emission from the central region of B0453–685 as seen by Chandra in the energy range 0.3–8.0 keV, smoothed to a resolution of 2″. The contours represent the 2.4 GHz image at full resolution (9″ × 8′4″), drawn at the levels of 2, 4, 6, 8, and 10 mJy beam\(^{-1}\); the rms sensitivity of these data is 70 mJy beam\(^{-1}\). Overlaid as vectors are the 2.4 GHz linearly polarized intensity at each position; the length of each vector is proportional to the polarized intensity (up to a maximum of 0.7 mJy beam\(^{-1}\)), and the orientation of the vector indicates the mean position angle of the electric field (averaged across the observing bandwidth and not corrected for Faraday rotation). The plus symbol indicates the center fitted for the surrounding SNR shell.]

![Table 1—Radio Properties of SNR B0453–685](\text{Extraction of table from text})
in these images. At the peak of nebular emission, the corresponding upper limit on a point source is 3 and 0.4 mJy at 1.4 and 2.4 GHz, respectively.

In the X-ray band, we employed the SHERPA package to carry out a two-dimensional fit to the nebular morphology. We fitted the core with three components: an elliptical Gaussian to define the overall shape, an unresolved source to represent an embedded pulsar, and a constant offset to account for background. Using these three components, we find that in the energy range 0.3–10 keV, the best-fit model contains 58 counts in an unresolved central source. While the apparent significance of this source seems high, we obtained equally good or better fits by replacing the unresolved component by a resolved Gaussian. This suggests a complex PWN morphology and only marginal evidence for a point source. Therefore, in subsequent discussion we adopt 58 counts as an upper limit, corresponding to a count rate of less than $1.5 \times 10^{-3}$ counts s$^{-1}$. Assuming a column density $N_{\text{H}} = 1.3 \times 10^{21}$ cm$^{-2}$ and a power-law spectrum with a photon index $\Gamma = 1.5$ (typical for a young pulsar), this corresponds to an unabsorbed X-ray luminosity (0.5–10 keV) $L_{\text{X}} < 6d_\odot^2 \times 10^{37}$ ergs s$^{-1}$.

These radio and X-ray upper limits on emission from a central pulsar are not especially constraining. Our radio limit is $\sim 40$ times above the upper limit for radio pulsations at this position from the survey of R. N. Manchester, G. Fan, A. G. Lyne, V. M. Kaspi, & F. Crawford (2003, in preparation). Several young pulsars have been recently identified with a point-source X-ray luminosity $L_{\text{X}} \approx 10^{32}$–$10^{33}$ ergs s$^{-1}$ (Murray et al. 2002; Hughes et al. 2003), well below the limit seen here.

In the absence of a direct detection, a first guess as to the properties of the pulsar in B0453–685 can come from comparison with other systems. There are $\sim 20$ other shell SNRs known to contain a central X-ray/radio PWN; of these other sources, the properties of B0453–685 most closely resemble those of the Vela SNR and of G0.9+0.1, as demonstrated in Table 2. The similarity of these three systems argues that SNR B0453–685 is most likely powered by a “Vela-like” pulsar (e.g., Kramer et al. 2003), with a spin-period $P \sim 100$ ms, a surface magnetic field $B \sim 3 \times 10^6$ G, and a spin-down luminosity $\dot{E} \approx 10^{37}$ ergs s$^{-1}$.

In cases in which a PWN has no identified pulsar, considerable further effort has been invested to infer the pulsar’s properties (i.e., current spin period $P$, initial period $P_0$, period derivative $\dot{P}$, and surface magnetic field $B$) from those of its PWN. The age, spin-down luminosity, and surface magnetic field of the system are, respectively,

$$
\tau = \frac{P}{n-1} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right],
$$

$$
\dot{E} = 4\pi^2 I \frac{\dot{P}}{P^2},
$$

$$
B = 3.2 \times 10^{19} (P \dot{P})^{1/2} G,
$$

where $I \equiv 10^{45}$ g cm$^2$ is the star’s moment of inertia, $n \equiv 2 - PP/\dot{P}^2$ is the “braking index,” and $P$ is in units of seconds. Typically, one assumes $n = 3$, $P_0 = 0$, and $L_X = \eta \dot{E}$ (where $\eta$ is an assumed efficiency factor). Values of $L_X$ and $\tau$ are determined from observations, from which estimates for $P$, $P_0$, and $B$ can then be derived using equation (1). Here we propose an alternative approach, where rather than assuming an (unphysical) value of $P_0$, we use the above expressions to eliminate $P$ and $P$, and thus obtain a relation between $B$ and $P_0$. Assuming that $B$ is constant with time, the resulting function has absolute maxima in both $B$ and $P_0$. The robust upper limits on the surface magnetic field and the initial spin period of the neutron star that result are

$$
B < 3.2 \times 10^{19} \frac{U}{\tau(n-1)} G,
$$

$$
P_0 < U [\tau(n+1)]^{-1/2} \frac{2}{n+1} 10^{(n-1)},
$$

where $U = P_{\text{d}}/\dot{P} = 4\pi^2 I h L_X$. These limits are reasonably insensitive to the value of $n$ assumed; for $2 < n < 3$ (encompassing the range for the four pulsars for which $n$ has been directly measured; e.g., Casares, Massaro, & Mineo 2003), we find $B < (3.1–6.3) \eta^{1/2} \times 10^{13}$ G and $P_0 < (448–488) \eta^{1/2}$ ms for this system. For other PWNs, a solid upper limit is $\eta < 0.05$; we have argued above that the pulsar here is “Vela-like,” for which $\eta = 0.01–0.001$ is more reasonable (Possenti et al. 2002). Thus we thus conclude that this pulsar has a surface magnetic field $B < 6 \times 10^{12}$ G and an initial spin period $P_0 < 50$ ms. These values are consistent with “typical” radio pulsars such as the Crab ($B = 4 \times 10^{12}$ G, $P_0 = 19$ ms) and Vela ($B = 3 \times 10^{12}$ G) pulsars, but not with the emerging class of young pulsars that are highly magnetized and/or slow initial rotators, such as PSRs J1846–0258 ($B = 5 \times 10^{13}$ G; Gotthelf et al. 2000) or J1210–5226 ($P_0 = 400$ ms; Pavlov et al. 2002).

3.2. Evolutionary State of the PWN

Chevalier (1998) divides PWN evolution into successive phases. The PWN first expands supersonically in the SNR interior. The PWN then collides with the SNR reverse shock; this compresses the PWN and causes it to expand more slowly. The pulsar’s motion can later become supersonic in the shocked SNR interior, and it then drives a bow shock.

If we assume that the pulsar spin-down luminosity is constant in the initial supersonically expanding phase, the radius of the PWN evolves such that $R_{\text{PWN}} = 0.839 \times (E_{0}/E_{57})^{1/5} V_{0} r$, where $V_{0}$ is the initial expansion velocity of the SNR (van der Swaluw et al. 2001). Here we observe $R_{\text{PWN}} \approx 3$ pc, $r \approx 13$ kyr and $E_{0} \approx 5 \times 10^{50}$ ergs, and we adopt $\dot{E} = E_{57} \times 10^{-27}$ ergs s$^{-1}$. Thus, if the PWN is still in this phase of evolution, we require $V_{0} \approx 700 E_{57}^{1/5}$ km s$^{-1}$, implying an enormous ejected mass $M_{\text{ej}} \approx 2E_{65} V_{0}/c \approx 100 E_{57}^{1/5} M_{\odot}$. We thus conclude that the PWN is almost certainly not expanding supersonically, having a radius much smaller than expected in this interpretation.

The brightest radio and X-ray emission from the PWN is offset from the SNR’s geometric center by $l = (2.7 \pm 0.5) d_\odot$, pc. Since this peak most likely marks the current position of the unseen pulsar, a possible interpretation is that the pulsar is moving away from its birth site with a transverse velocity $V_t = 4l/r = 200 \pm 40$ km s$^{-1}$. The radio PWN is clearly elongated, with a fading tail pointing back along the implied direction of motion. While this is suggestive of a bow shock morphology, this requires that the pulsar be moving supersonically through shocked ejecta. In the Sedov solution, this condition is met only when $l/R_{\text{SNR}} \approx 0.7$ (van der Swaluw, Achterberg, & Gallant 1998). Unless the pulsar’s motion is at least $\sim 20^\circ$ to the line of sight (implying a true velocity $V > 700$ km s$^{-1}$), the pulsar in this system is still too close to the center of its SNR to meet this requirement.

The remaining possibility is that this PWN has undergone a reverse shock interaction with its SNR and is now expanding subsonically. Such an interaction begins at an age $\sim 10$ kyr...
TABLE 2

| SNR          | Age (× 10³ yr) | R_SNR (pc) | R_PWN (pc) | L_R,PWN (× 10⁶ ergs s⁻¹) | L_X,PWN (× 10⁶ ergs s⁻¹) | References |
|--------------|---------------|------------|------------|--------------------------|--------------------------|-------------|
| B0453−685    | 13            | 29 ± 1     | 7 × 5      | 2                        | 0.8                      | 6           | 1           |
| Vela SNR     | ~11           | 42         | 10         | 0.8                      | 0.8                      | 2, 3        |
| G0.9+0.1     | ~10−20        | 20         | 6          | 7                        | 6                        | 4, 5        |

Notes.—R_SNR and R_PWN are the radii of the SNR and PWN, respectively; L_R,PWN and L_X,PWN are the approximate radio and X-ray luminosities, respectively, of the PWN.

The PWN luminosity quoted by Helfand et al. 2001 is much lower than this, but it corresponds to only the innermost component of the PWN.

References.—(1) This Letter; (2) Weiler & Panagia 1980; (3) Helfand et al. 2001; (4) Helfand & Becker 1987; (5) Porquet et al. 2003.

when \( M_{sw} \gtrsim 10 M_\odot \) (Chevalier 1998), consistent with the properties of this source. The elongated morphology and comparatively small radius seen for the radio PWN are simply accounted for by reverse-shock compression; the same properties have been similarly interpreted in the other SNRs listed in Table 2 (Blondin, Chevalier, & Frierson 2001).

4. CONCLUSIONS

New radio and X-ray observations of SNR B0453−685 in the LMC demonstrate this source to consist of both an outer shell and a central pulsar-powered nebula. We have used the properties of this SNR to infer that the unseen central engine is a typical young radio pulsar, with an initial period \( P_0 \sim 50 \text{ ms} \), a current period \( P \sim 100 \text{ ms} \), a surface field \( B \sim 6 \times 10^{12} \text{ G} \), and a spin-down luminosity \( \dot{E} \sim 10^{37} \text{ ergs s}^{-1} \). The small and elongated radio nebula results from compression of the PWN by the SNR reverse shock.

This study demonstrates that several useful constraints on the properties of an unseen pulsar can be inferred from those of its associated PWN and SNR, provided that good estimates for the system’s distance and age are available. With many new studies of PWNe and composite SNRs now emerging, such an approach can be applied to many other sources.

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