The Astronomical Journal, 121:3133–3137, 2001 June

PULSAR WIND NEBULAE AROUND THE SOUTHERN PULSARS PSR B1643−43 AND PSR B1706−44

E. B. Giacani[1]
Instituto de Astronomía y Física del Espacio (CONICET, UBA), Casilla de Correo 67, Sucursal 28, 1428 Buenos Aires, Argentina; egiacani@iafe.uba.ar
D. A. Frail and W. M. Goss
National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801; dfrail@nrao.edu, mgoss@nrao.edu
and
M. Vieytes
Instituto de Astronomía y Física del Espacio (CONICET, UBA), Casilla de Correo 67, Sucursal 28, 1428 Buenos Aires, Argentina; mary@sion.com
Received 2000 December 7; accepted 2001 February 13

ABSTRACT

We present high-resolution VLA images taken at the wavelengths of 20, 6, and 3.6 cm in the vicinity of the pulsars PSR B1706−44 (PSR J1709−4428) and PSR B1643−43 (PSR J1646−4346). Both of these pulsars are young (<30,000 yr) and have large spin-down luminosities ($\dot{E} > 10^{35}$ ergs s^{-1}) and hence are good candidates to search for extended synchrotron nebulae excited by the relativistic pulsar wind. For PSR B1643−43 we found evidence of a 4′ comet-shaped nebula, suggestive of a synchrotron "wake" left by a fast-moving pulsar. PSR B1706−44 appears surrounded by a spherical nebula approximately 3′ in diameter. Based on their morphology, the detection of significant linear polarization (>20%), and their flat radio spectra ($\alpha = 0.25$–0.3, where $S_\nu \propto \nu^{-\alpha}$), we argue that these are wind nebulae powered by the rotational energy loss of the respective pulsars.

Key words: ISM: general — pulsars: individual (PSR 1643−43, PSR 1706−44) — supernova remnants

1. INTRODUCTION

Pulsars transfer the bulk of their rotational angular momentum in a wind of relativistic particles and Poynting flux (Michel 1969; Rees & Gunn 1974; Kennel, Fujimura, & Okamoto 1983). However, because the particles emerge from the magnetosphere with zero pitch angle, the winds cannot be directly observed. Therefore to study the winds from pulsars it is necessary to study the synchrotron emission from the pulsar wind nebula (PWN) produced when the wind is thermalized as it comes into pressure equilibrium with the surroundings. The Crab Nebula is the archetype of the PWNs; this source has been studied in detail at all wavelengths (e.g., X-ray, Brinkmann, Aschenbach, & Langmeier 1985; radio, Bietenholz & Kronberg 1992; optical, Hester et al. 1995). The fact that the bolometric luminosity of the Crab Nebula requires an ongoing source with power comparable to the rotational energy loss ($\dot{E}$) of the pulsar shows that the PWN owes its existence to the existence of a young, energetic pulsar.

At radio wavelengths, there are at least two morphological types of PWNs, depending on the source of confinement for the wind (Frail & Scharringhausen 1997; Chevalier 1998; Gaensler et al. 2000): the so-called filled-center and the bow shock. The filled-center PWNs or "plerions" (e.g., the Crab) are inside young supernova remnants and are confined by the hot gas driving the expansion. The bow shock PWNs are found both inside and outside supernova remnants (e.g., PSR B1757−24 and G5.4−1.2; Frail & Kulkarni 1991) and are confined by the high space velocities of the pulsar. The nonthermal radio emission from PWNs can be distinguished from shock-accelerated emission in supernova remnants by (1) a flat spectrum, $\alpha = 0.1$ to 0.3, where $S_\nu \propto \nu^{-\alpha}$, and (2) a high degree of linear polarization ($\gg 5$%) (Chevalier 1998).

The existing sample of radio PWNs is small. There are no more than seven confirmed PWNs at radio wavelengths (the number is comparable to that for X-ray PWNs) that contain a known pulsar. Frail, Goss, & Whiteoak (1994, hereafter FGW94) made radio images around three young pulsars and identified two promising PWN candidates, based on their morphology alone. In this paper we present multifrequency polarimetric observations made with the National Radio Astronomy Observatory[2] (NRAO) Very Large Array (VLA) toward PSR B1643−43 and PSR B1706−44 to ascertain better the properties of the emission in the vicinity of these pulsars.

2. OBSERVATIONS

The extended emission in the vicinity of PSR B1643−43 and PSR B1706−44 was imaged at 1425, 4860, and 8460 MHz in several observing runs during 1997, using different configurations of the VLA (see Table 1). The data were obtained in the Stokes parameters I, Q, U, and V. The uv data from each array were combined to form a single data set for each pulsar to image a full range of spatial frequencies. An additional 1.4 GHz data set, taken in 1993 with the VLA in its CnB and DnC hybrid configurations, was extracted from the archive. A description of these data can be found in FGW94. All data reduction and calibration were done following standard practice in use at the VLA. The images were corrected for the primary beam. Table 1 summarizes the observational parameters.

3. RESULTS

3.1. *PSR B1643−43*

PSR B1643−43 (PSR J1646−4346) is a 232 ms pulsar, with a characteristic age 32.6×10^3 yr, a spin-down luminosity 3.6×10^{35} ergs s^{-1} (Johnston et al. 1995), and a

[1] Member of the Carrera del Investigador Científico of CONICET, Argentina.

[2] The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

TABLE 1

OBSERVATIONAL PARAMETERS

Parameter	1425 MHz	4860 MHz	8460 MHz
VLA configuration	BnA + CnB + DnC	CnB + DnC	CnB + DnC
Observing dates	1997 Feb 7, 8	1997 Jun 15	1997 Jun 16, 17
	1993 Jun 2, 1997 Jun 13	1997 Oct 14	1997 Oct 6, 10
	1993 Oct 14, 1997 Oct 17		
Total observing time (hr)	7 + 17.5 + 14	17.5 + 14	17.5 + 14
Calibrators	3C 286, 1622-297	3C 286, 1622-297	3C 286, 1622-297
Synthesized beam (arcsec):			
PSR B1643−43	27 × 10	16 × 6	19.4 × 14
PSR B1706−44	24 × 9	16 × 6	14 × 8
rms (mJy)	0.04	0.04	0.04

dispersion measure–based distance of 6.9 kpc (Taylor & Cordes 1993). A search for pulsed γ-ray emission was made with the EGRET and COMPTEL instruments on board the Compton Gamma-Ray Observatory, with null results (Thompson et al. 1994; Carramiñana et al. 1995).

Based on observations carried out with the VLA in the radio continuum at 20 cm in an extended region around PSR B1643−43, FGW94 have shown that the pulsar is located within the shell of supernova remnant (SNR) G341.2+0.9, about 8′ west of the center of the remnant (see Fig. 1, *left*). Morphological evidence and a coincidence in distance led FGW94 to propose a physical association between the pulsar and the remnant. FWG94 have also reported the detection of a 4′ nebulosity with a cometary morphology just east of PSR B1643−43 that is joined to the pulsar by a bridge of emission. Based on morphological evidence the authors suggested that this feature is the synchrotron nebula left behind by the fast-moving pulsar. The characteristic age of PSR B1643−43 and its positional offset from the center of G341.2+0.9 together imply a transverse velocity of 475 km s^{-1}, which in the absence of proper-motion measurements predicts that the pulsar would have to be moving about 15 mas yr^{-1} (FGW94).

In the same survey, FWG94 noted that the position of PSR B1643−43 most likely coincided with a 1.5 mJy point source detected in their 20 cm VLA radio image. Their interferometric position differed significantly (40″) from the timing position of the pulsar (Johnston et al. 1995). The later is probably an error due to the timing noise and glitches that characterize the spin-down of young pulsars. The present observations, performed with better sensitivity and spatial resolution than in FGW94, allow us to derive an improved interferometric position for the pulsar. Our best position determination is from the BnA array 20 cm data with a beamwidth of 7″.3 × 3″.7, a considerable improvement over the 25″ beam in FGW94. A fit to the peak gives the position (epoch B1950.0) R.A. = $16^h43^m16^s.56 \pm 0^s.04$, decl. = $-43°40'31''.8 \pm 0''.8$, or (epoch J2000.0) R.A. = $16^h46^m50^s.86 \pm 0^s.04$, decl. = $-43°45'53''.7 \pm 0^s.8$. We have also determined the position of the pulsar using each data set separately and at all frequencies and find good agreement. The derived position is about 5″ northwest of the position given by FWG94. We suspect that extended nebular emission underlying the pulsar is shifting the centroid, and therefore the present position with its much smaller beam is superior to that of FGW94.

Figure 1 (*right*) shows gray-scale and contour images of a region surrounding PSR 1643−43 at 1.4 and 4.8 GHz. These images were convolved to a 25″ circular beam. The cross indicates the new position of the pulsar. Because of the incomplete sampling of the visibility plane, the VLA image at 8.4 GHz lacks short spacings and is not included here.

From Figure 1 (*right*) a synchrotron nebula of about 3′ in size is clearly visible. The nebula, with the pulsar located at its western border, appears as a feature pointing back from the pulsar to the center of G341.2+0.9 in the direction opposite the pulsar's implied proper motion. Such a morphology is compatible with the interpretation of this structure as a PWN. Similar radio morphologies have previously been detected surrounding PSR B1757−24 in the SNR G5.4−1.2 (Frail & Kulkarni 1991) and PSR B1853+01 in W44 (Frail et al. 1996).

We find additional evidence to support our contention that this feature is the PWN associated with PSR B1643−43. (1) We detect significant linearly polarized intensity at 4.8 and 8.4 GHz, with a mean fractional polarization of about 30%. (2) We also estimate the total flux density for the nebular emission (and for the pulsar). These values are given in Table 2. The errors quoted include the rms noise of each image and the uncertainty in the choice of the integration boundaries. From a least-squares fit we derive a radio spectral index $\alpha = 0.24$ between 330 MHz and 4.8 GHz, in which the data at 330 MHz were taken from FWG94 and the data at 843 MHz were taken from the Molonglo Observatory Synthesis Telescope survey by Green et al. (1999). A high degree of linear polarization and a flat radio spectral index are two unmistakable properties of PWNs in the radio band, and thus we propose that this is the synchrotron nebula excited by the pulsar wind.

For a distance of 6.9 kpc, the corresponding radio luminosity L_r of the PWN between 10^7 and 10^{11} Hz is

TABLE 2

OBSERVED PARAMETERS OF THE PULSAR WIND NEBULAE

Pulsar and ν (GHz)	S_{PSR} [a] (mJy)	S_{PWN} [b] (mJy)
B1643−43:		
1.42	1.0 ± 0.2	31 ± 13
4.86	0.10 ± 0.03	23 ± 4
B1706−44:		
1.42	11.0 ± 0.2	28 ± 11
4.86	2.0 ± 0.7	28 ± 6
8.46	0.8 ± 0.1	11 ± 3

[a] Flux density of the pulsar.

[b] Integrated flux density of the PWN.

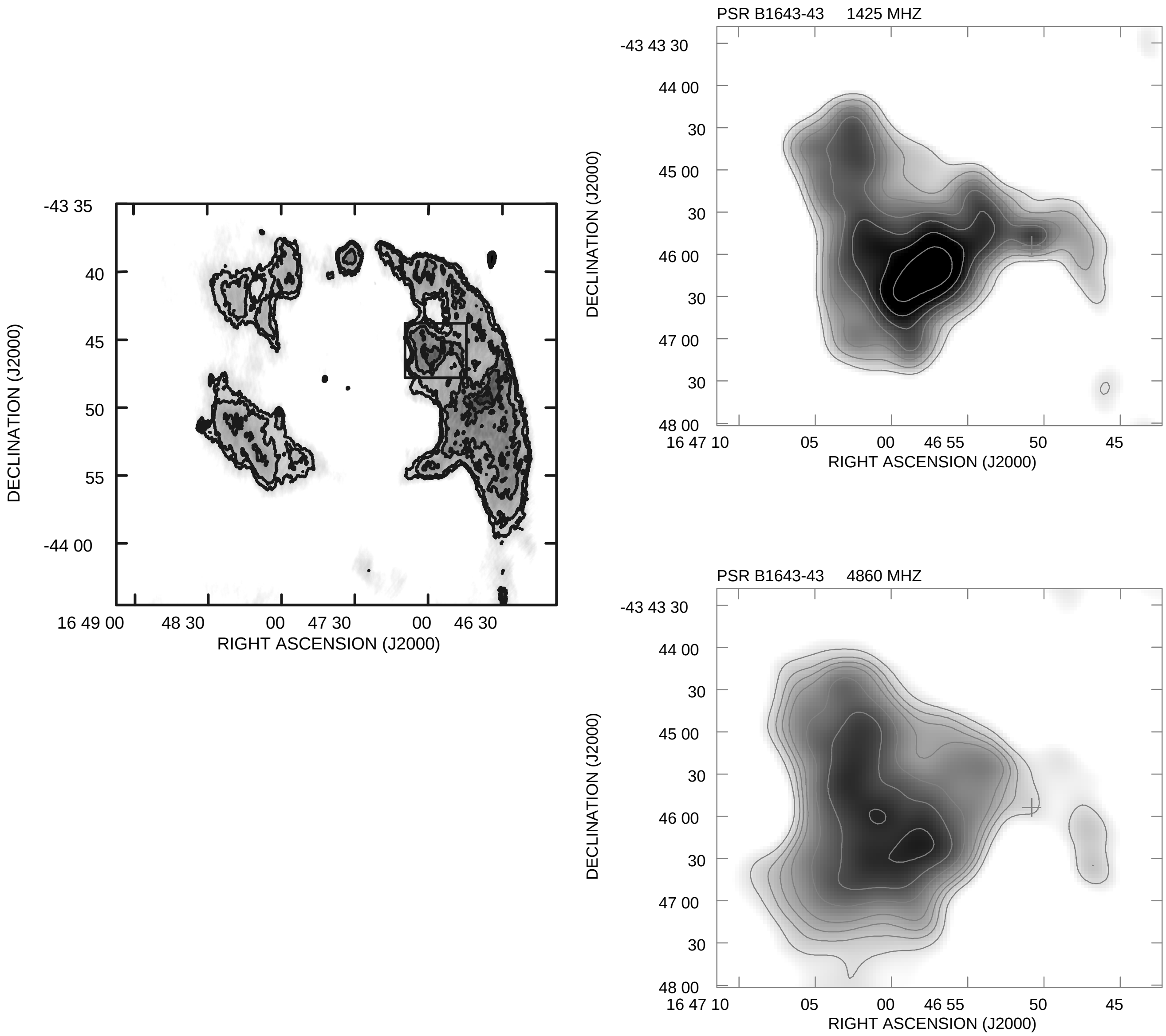

Fig. 1.—*Left*: VLA continuum image of the SNR G341.2+0.9 at 20 cm from Frail, Goss, & Whiteoak (1994), showing extended radio emission surrounding PSR B1643−43 (*box*). *Top right*: Gray-scale and contour image of the region surrounding PSR B1643−43 at 1425 MHz, showing the location of the pulsar (*cross*) as derived in this paper. The plotted contours are 4.2, 4.5, 4.8, 5.1, 5.4, 5.7, and 6.0 mJy beam^{-1}. The beam size is 25″. The gray scale ranges from 4 to 5.8 mJy beam^{-1}. *Bottom right*: Same region at 4860 MHz, showing the location of the pulsar (*cross*). Contour levels are at 0.16, 0.3, 0.4, 0.5, 0.7, 0.9, and 1.1 mJy beam^{-1}. The gray scale ranges from 0 to 1.3 mJy beam^{-1}.

8.3×10^{31} ergs s^{-1}. This value corresponds to the efficiency $\epsilon \equiv L_r/\dot{E} = 1.6 \times 10^{-4}$, in very good agreement with the value $\epsilon \sim 10^{-4}$ derived by Gaensler et al. (2000) for young energetic pulsars.

3.2. *PSR B1706−44*

PSR B1706−44 (PSR J1709−4428) is a young pulsar (spin-down age ∼17,000 yr) with a period of 102 ms and a large spin-down luminosity of 3.4×10^{36} ergs s^{-1}. It is also one of a very small number (six) of radio pulsars to have been detected as a pulsed gamma-ray source (Thompson et al. 1992). There are several lines of evidence that suggest the existence of a filled-center nebula surrounding the pulsar. FGW94 have noted in a low-resolution (24″) radio image at 20 cm that PSR B1706−44 appears embedded in a "halo" about 4′ in size. The authors suggest that the emission could be due to a PWN around the pulsar. In the soft X-ray band, between 0.1 and 2.4 keV, unpulsed radiation was detected, with a 2 σ upper limit on the pulsed fraction of 18%. This unpulsed emission is thought to originate from a compact synchrotron nebula about 1′ in size around the pulsar (Becker, Brazier, & Truemper 1995; Finley et al. 1998). More recent X-ray observations made with *ROSAT*, *ASCA* (Finley et al. 1998) and *RXTE* (Ray, Harding, & Strickman 1999) confirm the lack of pulsations. Observations of PSR B1706−44 in the very high energy γ-rays by the CANGAROO imaging Cerenkov telescope have revealed unpulsed TeV radiation at a 10 σ confidence level (Kifune et al. 1995). It was suggested that the TeV emission could be due to inverse Compton radiation from a PWN (Harding

1996; Aharonian, Atoyan, & Kifune 1997). Chakrabarty & Kaspi (1998) have reported negative results of a search for optical pulsations from PSR B1706−44. Sefako et al. (2000) have carried out V-band CCD observations in the direction of the pulsar to look for the optical counterpart of the 1′ compact X-ray nebula, but their search did not reveal any nebular structure around the pulsar.

A possible association between the SNR G343.1−2.3 and PSR B1706−44 was proposed by McAdam, Osborne, & Parkinson (1993). Such an association, however, was questioned by FGW94 and Nicastro, Johnston, & Koribalski (1996), based on distance inconsistencies, a lack of morphological signatures of interaction between the pulsar and the SNR, and scintillation measurements indicating a transverse velocity for the pulsar at least 20 times smaller than that required if the pulsar originated in the geometric center of G343.1−2.3 about 17,000 yr ago.

A dispersion-based distance measure of Taylor & Cordes (1993) places PSR B1706−44 at 1.8 kpc, while H I absorption shows that its distance lies in the range 2.4–3.2 kpc (Koribalski et al. 1995). In what follows we will adopt a distance to the pulsar of 2 kpc.

As in the previous case for PSR B1643−43, we have determined the position of the pulsar by using all data sets separately. Here again, the most accurate fit was obtained from the high angular resolution of the BnA array 20 cm data (beamwidth $9''.1 \times 4''.8$). The derived position (epoch B1950.0) is R.A. = $17^h6^m5^s.09 \pm 0^s.02$, decl. = $-44°25'20''.6 \pm 0''.5$ or (at epoch J2000.0) R.A. = $17^h9^m42^s.75 \pm 0^s.02$, decl. = $-44°29'6''.6 \pm 0''.5$. This position is in good agreement with the interferometric measurements of FGW94 and the new timing position by Wang et al. (2000).

Figure 2 shows gray-scale and contour images of the region surrounding the pulsar at 1425, 4860, and 8640

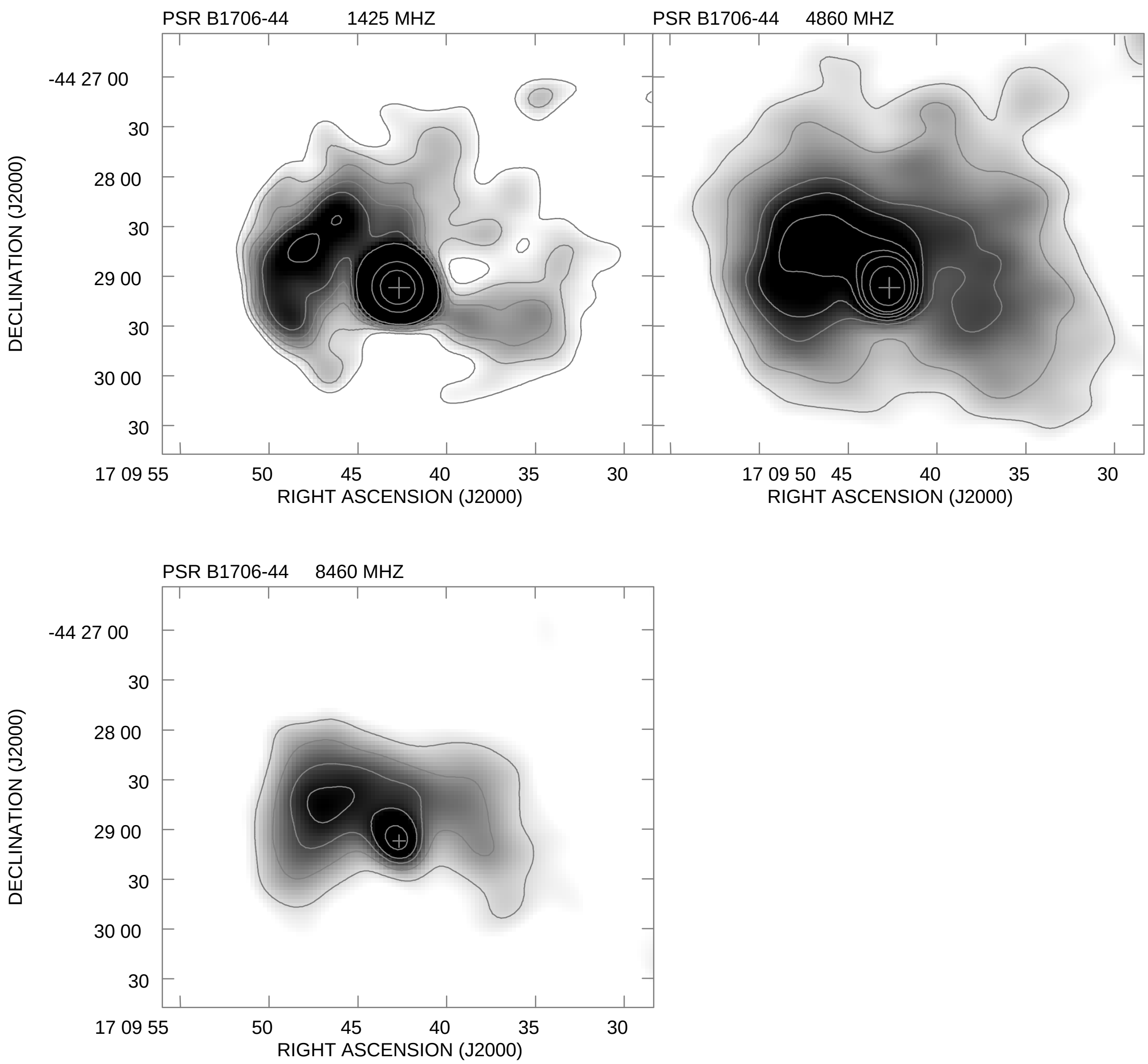

FIG. 2.—*Top left*: Gray-scale and contour image of the region surrounding PSR B1706−44 at 1425 MHz, showing the position of the pulsar as derived in this paper (*cross*). The plotted contours are 2.1, 2.25, 2.4, 2.55, 2.7, 3.0, 6.0, and 9.0 mJy beam^{-1}. The beam size is 25″. The gray scale goes linearly from 2.1 to 2.9 mJy beam^{-1}. *Top right*: Same region at 4860 MHz, showing the position of PSR B1706−44 (*cross*). The contours are 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, and 1.5 mJy beam^{-1}. The beam size is 25″. The gray scale ranges from 0 to 1 mJy beam^{-1}. *Bottom*: The same region around PSR B1706−44 at 8460 MHz, showing the position of the pulsar (*cross*). The contour levels are 0.1, 0.3, 0.5, 0.65, 0.9, and 1.1 mJy beam^{-1}. The gray scale ranges from 0 to 0.7 mJy beam^{-1}.

MHz. These images were convolved with a circular beam of 25″. The cross indicates the position of PSR B1706−44. The pulsar appears surrounded by a synchrotron nebula, about 3′5 × 2′5 in size, with the brightest part toward the east.

The total flux density of the nebular emission and PSR B1706−44 is summarized in Table 2. Again, the quoted errors take into account uncertainties in the definition of the outer boundaries. From a least-squares fit we derive a radio spectral index $\alpha = 0.3$ between 330 MHz and 8.4 GHz, in which the data at 330 MHz were taken from FWG94. Significant linearly polarized intensity was detected at 4.8 and 8.4 GHz, with a mean fractional polarization of about 20%. This is convincing evidence that we have detected another PWN.

The radio luminosity L_r of the PWN between 10^7 and 10^{11} Hz is 7.6×10^{30} ergs s^{-1}, corresponding to an efficiency $\epsilon \equiv L_r/\dot{E} \approx 2 \times 10^{-6}$. These values are significantly lower than for any other radio PWN (Frail & Scharringhausen 1997). The equipartition magnetic field in the nebula can be estimated by the usual means (Pacholczyk 1970), assuming that the energy density of the magnetic field is half the total synchrotron pressure. For an electron-positron plasma with unity volume filling factor we find $B_{\rm eq} = 20\ \mu$G and a minimum energy of 3×10^{45} ergs.

To match the observed X-ray and γ-ray fluxes in PSR B1706−44, Harding (1996) proposed a scenario in which the TeV emission is produced within the synchrotron nebula via the IC mechanism and the target photon field is the 2.7 K microwave background radiation (MBR). The author obtains a good fit if the magnetic field strength inside the nebula is lower than 5 μG, a value lower than our estimation.

On the other hand, Aharonian et al. (1997) proposed that the production of TeV γ-rays takes place in a region of about 0°1, outside the compact X-ray nebula. Inside the compact nebula, where synchrotron is the dominant process, the magnetic field takes values between 20 and 60 μG (depending on the model parameters); out of this region, where the MBR photons are accelerated to TeV energy by the IC mechanism, the value of the magnetic field is about 3 μG.

Our estimate of the magnetic field in the radio nebula is in good agreement with that of the Aharonian et al. model for the compact X-ray nebula. However, these new radio observations indicate that the synchrotron nebula extends up to 3′5. The γ-photons would therefore need to be produced even farther out.

Finley et al. (1998) have also explained the unpulsed TeV emission in PSR B1706−44 as originated by the IC mechanism, but in their model the target photon field is the infrared background radiation. Their results are consistent with a continuous unbroken power-law spectrum extending from the radio to the X-ray domain. However, the current radio data argue against this model. Our observations allow us to define better the radio spectrum producing $\alpha \simeq 0.3$, which when combined with that obtained from the X-ray observations implies the existence of at least one break in the synchrotron spectrum between the radio and X-ray bands.

4. CONCLUSIONS

We have made radio observations toward PSR B1643−43 and PSR B1706−44 and found good evidence that these pulsars are surrounded by extended emission powered by their winds. At the time of the survey of Frail & Scharringhausen (1997) only six PWNs were known. This present work and Gaensler et al. (1998) have extended this sample by 50%. These new radio PWNs have the same properties of the rest of the sample (i.e., morphology, spectra, and polarization) as a whole with one exception. Most radio PWNs radiate on the order of 10^{-4} of their spin-down luminosity, but there are a large number of non-detections (Gaensler et al. 2000) suggesting that this ratio is not constant and may be in fact much lower in specific cases. PSR B1706−44 and PSR B0906−49 both have a PWN with ϵ ($\simeq 2 \times 10^{-6}$), much lower than the rest of the sample but comparable to those inferred from the upper limits of other young pulsars. In the case of PSR B0906−49, the spectrum of the radio nebula is steeper than that of other radio PWNs and the pulsar is older than any other pulsar known to power a radio PWN. Clearly we need further broadband studies of PWNs produced under a variety of conditions to understand better how the radio emission from a PWN is produced and how it depends on the properties of its pulsar.

This research was funded by a Cooperative Science Program between the National Science Foundation and CONICET (Argentina) and through CONICET grant 4203/96 and ANPCYT grant 0300000-0235.

REFERENCES

Aharonian, F. A., Atoyan, A. M., & Kifune, T. 1997, MNRAS, 291, 162
Becker, W., Brazier, K. T., & Truemper, J. 1995, A&A, 298, 528
Bietenholz, M. F., & Kronberg, P. P. 1992, ApJ, 393, 206
Brinkmann, W., Aschenbach, B., & Langmeier, A. 1985, Nature, 313, 662
Carramiñana, A., et al. 1995, A&A, 304, 258
Chakrabarty, D., & Kaspi, V. M. 1998, ApJ, 498, L37
Chevalier, R. A. 1998, Mem. Soc. Astron. Italiana, 69, 977
Finley, J. P., Srinivasan, R., Saito, Y., Hiriyama, M., Kamae, T., & Yoshida, K. 1998, ApJ, 493, 884
Frail, D. A., Giacani, E. B., Goss, W. M., & Dubner, G. M. 1996, ApJ, 464, L165
Frail, D. A., Goss, W. M., & Whiteoak, J. B. Z. 1994, ApJ, 437, 781 (FGW94)
Frail, D. A., & Kulkarni, S. R. 1991, Nature, 352, 785
Frail, D. A., & Scharringhausen, B. R. 1997, ApJ, 480, 364
Gaensler, B. M., Stappers, B. W., Frail, D. A., & Johnston, S. 1998, ApJ, 499, L69
Gaensler, B. M., Stappers, B. W., Frail, D. A., Moffett, D. A., Johnston, S., & Chatterjee, S. 2000, MNRAS, 318, 58
Green, A. J., Cram, L. E., Large, M. I., & Ye, T. 1999, ApJS, 122, 207
Harding, A. K. 1996, Space Sci. Rev., 75, 257
Hester, J. J., et al. 1995, ApJ, 448, 240
Johnston, S., Manchester, R. N., Lyne, A. G., Kaspi, V. M., & D'Amico, N. 1995, A&A, 293, 795
Kennel, C. F., Fujimura, F. S., & Okamoto, I. 1983, J. Astrophys. Geophys. Fluid. Dyn., 26, 147
Kifune, T., et al. 1995, ApJ, 438, L91
Koribalski, B., Johnston, S., Weisberg, J. M., & Wilson, W. 1995, ApJ, 441, 756
McAdam, W. B., Osborne, J. L., & Parkinson, M. L. 1993, Nature, 361, 516
Michel, F. C. 1969, ApJ, 158, 727
Nicastro, L., Johnston, S., & Koribalski, B. 1996, A&A, 306, L49
Pacholczyk, A. G. 1970, Radio Astrophysics (San Francisco: Freeman)
Ray, A., Harding, A. K., & Strickman, M. 1999, ApJ, 513, 919
Rees, M. J., & Gunn, J. E. 1974, MNRAS, 167, 1
Sefako, R. R., de Jager, O. C., Van der Walt, D. J., & Winkler, H. 2000, preprint (astro-ph/0003449)
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Thompson, D. J., et al. 1994, ApJ, 436, 299
———. 1992, Nature, 359, 615
Wang, N., Manchester, R. N., Pace, R. T., Bailes, M., Kaspi, V. M., Stappers, B. W., & Lyne, A. G. 2000, MNRAS, 317, 843