1. INTRODUCTION

PSR B1706−44, discovered by Johnston et al. (1992), is among the most interesting pulsars for study at high energies. It is one of a handful of pulsars detected by the Energetic Gamma-Ray Experiment Telescope (EGRET) in GeV γ-rays. It is quite similar to the Vela pulsar, with a characteristic age \( \tau_c = P(2P) = 1.7 \times 10^8 \) yr and a spin-down luminosity of \( \dot{\gamma} = 10^{36} \) ergs s\(^{-1}\). However, a prominent H\(_2\) emission feature seen in the bright limb of G343.1−2.3 at \( 2.3 \) kpc (McAdam et al. 1996) is not seen by Johnston et al. (1993). The pulsar dispersion measure (DM) gives a distance of \( 2.3 \pm 0.3 \) kpc. Ichimaru et al. (1993) have proposed an improved distance estimate of \( 3 \pm 0.6 \) kpc in the Cordes & Lazio (2002) model. Model & Golap (2002) have argued for an association. In particular, they found a faint southern extension of the SNR, which would place the pulsar within the full SNR boundary. They also noted an approximately north-south elongation of the X-ray PWN, pointing roughly back to the SNR center, and argued that this would represent a trailed nebula. The required velocity for travel from the approximate geometric center of the SNR, about 12\(^\circ\) away, was \( \sim 10000 \) km s\(^{-1}\), where \( \tau_4 \) is the age in units of \( 10^4 \) yr. There are, however, some challenges to this SNR association. Koribalski et al. (1995), in an H\(_i\) absorption study of the pulsar, found velocity components setting lower and upper bounds for the distance of \( d_{\text{min}} = 2.4 \pm 0.6 \) kpc and \( d_{\text{max}} = 3.2 \pm 0.4 \) kpc. However, a prominent H\(_i\) emission feature seen in the bright limb of G343.1−2.3 at \( 32 \) km s\(^{-1}\) is not seen by Koribalski et al. in the absorption spectrum of the pulsar, suggesting that it lies in front of the SNR. Also, scintillation studies (Nicastro et al. 1996; Johnston et al. 1998) suggest a low transverse velocity for the pulsar, \( v < 89 \) km s\(^{-1}\). This estimate has been supported by more recent scintillation measurements (S. Johnston 2004, private communication). Thus, the distances of the pulsar and the SNR are still fairly uncertain. We adopt here a generic distance of \( 3 \) kpc in the discussion that follows but carry through the scaling to show the distance dependence.

We have obtained a deeper 100 ks ACIS-I exposure of PSR B1706−44 and its surroundings. The X-ray exposure coverage is compared to the overall geometry of G343.1−2.3 in Figure 1. Together with new ATCA radio continuum imaging, we are able to study the rich structure in this PWN and further constrain its connections with the SNR.

2. OBSERVATIONS AND DATA ANALYSIS

PSR B1706−44 was observed with the Chandra ACIS-I array (four ACIS-I chips, along with the S3 and S4 chips) on 2004 February 1−2 with standard imaging (3.2 s TE) exposures. The CCD array was operated in “very faint” (VF) mode, allowing improved rejection of particle backgrounds. The total live time was 98.8 ks, and no episodes of strong background flaring were observed. Hence, all data are included in our analysis. The pulsar was positioned near the standard aim point of the I3 chip, and all observing conditions were normal. We have also compared our new exposure with the archival (2001 February 3) 14.3 ks ACIS-S3 exposure (ObsID 0757). As usual, the backside-illuminated S3 chip suffered more from particle background, and after cutting out periods of background flares, 11 ks of clean exposure...
remained. All analysis was performed using CIAO version 3.2 and CALDB version 3.0.0, including automatic correction for the ACIS quantum efficiency degradation. These data were nearly free of pile-up; the maximum pixel counts at the pulsar position indicate only 2.5% pile-up, while the best-fit model for the point source has an expected pile-up fraction of \( \frac{C_24}{3.5\%} \). For sources with low pile-up we can maximize the spatial resolution of the ACIS image by removing the standard pixel randomization and applying an algorithm correcting the position of split pixel events (Mori et al. 2001). This decreases the on-axis point-spread function (PSF) width in our data set by \( \geq 10\% \). These data are compared with radio observations of the PWN.

2.1. Radio Imaging and Astrometry

Data for the radio maps shown here were collected at the Australia Telescope Compact Array (ATCA) in Narrabri (latitude \( -30^\circ 3 \), Frater et al. 1992). For the 1.4 GHz map in Figures 1 and 2 (left), the data acquisition and analysis are described in Dodson & Golap (2002). For the image contours in Figure 3 (left), the data first presented in Dodson & Golap (2002) were reimaged, including the 6 km baselines and uniform weighting to highlight the high-resolution features. The restoring beam size is \( 9'0 \times 7'8 \). To show the nebular structure, an 11 mJy point-source PSF has been subtracted at the position of the pulsar. Two maxima appear flanking the pulsar position. These are unlikely to be artifacts due to pulsar variability, as diffractive scintillation for this pulsar is particularly weak (Johnston et al. 1998). Since the data were collected in five sessions, spread over more than a year, it is in principle possible for slow refractive scintillation to change the pulsar flux between epochs and distort its PSF. However, each epoch used \( \sim 12 \) hr of integration, so any residual epoch PSF should be close to circularly symmetric, in contrast to the structure near the pulsar, which is clearly bipolar. Further observations, with pulsar binning, have been requested to confirm this result.

For the 4.8 GHz map in Figure 2 (right), observations were made at 4.8 and 8.6 GHz with the array in the standard configurations 0.75A, 1.5A, and 6A on 2002 January 6, February 16, and April 11. The maximum and minimum baselines for the 4.8 GHz data were 1 and 100 k\( \lambda \) (angular resolutions of \( 3'4--2''1 \) for a total of 26 hr of observation. In all cases we observed the two frequencies with bandwidths of 128 MHz. We used the Australia Telescope National Facility (ATNF) correlator mode that divides each integration’s data into separate phase bins spanning the pulsar period. First, this allowed the strongly pulsed point-source flux to be excluded from the image, and second, it allowed us to self-calibrate using the relatively strong point-source flux from the pulsar. After data editing and calibrating, we

![Fig. 1.—Gray-scale image of our new ACIS-I pointing of PSR B1706–44. The contours (at 8, 10, 12 and 14 mJy beam\(^{-1}\)) show the shell of G343.1–2.3 from a 19 pointing 1384 MHz ATCA mosaic (Dodson & Golap 2002). The radio map has a resolution of \( 70'' \times 47'' \) and an rms final map noise of 0.6 mJy. The X-ray PWN lies on a spur of radio emission. An approximate boundary of the full SNR (25' radius) and an arrow for the inferred PSR motion, assuming birth at the SNR center, are shown.](image1)

![Fig. 2.—Left: ACIS-I 1–7 keV image with point sources (other than the pulsar) removed, exposure correction applied, and 20' Gaussian kernel smoothing. Contours are from the 1.38 GHz radio map of Fig. 1. Right: 1.5 Gaussian-smoothed image of the PWN with an overlay of the core of the radio nebula from a 4.8 GHz ATCA image (contours at 0.4, 0.8, 1.0, 1.1, \ldots, 1.6 mJy beam\(^{-1}\)); the resolution is 20', and the image rms is 0.2 mJy beam\(^{-1}\).](image2)
inverted the image with a re-taper of 20′′ and deconvolved it with the full-polarization maximum entropy task PMOSMEM in MIRIAD.

The most important test of the SNR association would, of course, be a direct astrometric proper motion. With a 1.4 GHz flux of ~11 mJy, PSR B1706–44 is relatively bright. As such, it is suitable for phase-referenced very long baseline interferometry (VLBI) astrometry, if an in-beam reference could be found. Unfortunately, searches for phase references adequate for Australian Long Baseline Array (LBA) and US Very Long Baseline Array (VLBA) experiments have not detected comparison sources with compact fluxes greater than ~1 mJy. Attempts were made at external phase reference VLBA astrometry. However, at 1.4 GHz, the nearest known reference source (2′5 away) was scatter-broadened to ~50 mas. With the strong ionosphere at such low elevation, the next nearest known source (10′′ away) is too distant for effective calibration. Since the pulsar spectrum is steep, an attempt at VLBA astrometry at 5 GHz was also unsuccessful; at this low elevation the system temperature was 4–5 times nominal and only six VLBA antennae could be used, reducing the sensitivity to ~15% of nominal. So unfortunately we have only tied-array astrometry at present. Even if the pulsar does travel from the geometric center of G343.1–2.3, the expected proper motion is only ~40 mas yr⁻¹; the existing time base of VLA and ATCA imaging does not yet allow a serious constraint on this motion. We must conclude that a direct proper-motion measurement awaits substantially increased (Square Kilometer Array [SKA] or Extended Very Large Array [EVLA]) capabilities and a long-duration, large-baseline experiment.

2.2. X-Ray Spatial Analysis

To show the diffuse emission surrounding PSR B1706–44, we plot (Fig. 2, left) a 1–7 keV image with point sources removed (except the pulsar). These data are exposure corrected to minimize the chip gaps and are heavily smoothed on a 20′′ scale. The diffuse emission is an edge-brightened, radius ~110′′ cavity surrounding the pulsar with a faint extension to the west. Contours of the 1.38 GHz radio map show good correlation with the radio emission in the bar crossing G343.1–2.3 (Fig. 1). We refer to this structure as the “nebula.”

Moving into smaller scales, in Figure 2 (right) we show a 1–7 keV image smoothed with a 1′5 Gaussian. Point sources have not been removed. This shows that the cross structure fitted by Ng & Romani (2004) extends across ~1′. Narrow X-ray jets, which we refer to here as the “outer jet” (extending south) and the “outer counterjet” (extending north) start ~10′′ from the pulsar and continue to ~30′′. Bracketing these is faint diffuse X-ray emission that we call the “equatorial PWN.” For comparison, we draw contours of a 4.8 GHz ATCA image with a 21′′ × 18′′ restoring beam. These observations have the pulsar “gated out” and show that the radio PWN has a hollow center bracketing the equatorial PWN. Diffuse radio peaks are, in fact, seen just east and west of this X-ray structure.

Finally, we show in Figure 3 a lightly smoothed image of the central region of the PWN, stretched to bring out the faint outer jets. The contours are drawn from a 1.38 GHz ATCA image, where the 6 km baselines have been weighted to produce a 9′0 × 7′8 restoring beam. A point-source PSF has been subtracted at the pulsar position. Two local radio maxima with peak fluxes of ~2 and ~2.5 mJy bracket the “torus” structure. The radio then shows a subluminous zone surrounding the equatorial PWN; beyond ~30′′ the radio brightens again, as in Figure 2 (right). No emission appears along the outer jets. Indeed, there appear to be evacuated channels in the radio emission, but improved signal-to-noise ratio (S/N) and resolution are needed to probe this submillijansky structure. Figure 3 (middle) shows the innermost region of the PWN with the best-fit torus plus inner jet model (see § 2.3).

The overall geometry of the PWN is strongly reminiscent of that surrounding the Vela pulsar. In particular Pavlov et al. (2003) have described a series of ACIS images of the Vela nebula that show a torus-like structure, an inner jet and counterjet, and a faint narrow outer jet system. This imaging sequence showed...
that the Vela outer jet, which is patchy and strongly bent, varies dramatically on timescales of days to weeks. Apparent motion of blobs within the jets suggests mildly relativistic bulk velocities and strong instabilities. For PSR B1706−44, our single sensitive image does not let us comment on variability. However, we argue that the relatively straight and narrow jets, ~3 times longer than those of Vela, and the symmetric PWN structure are a consequence of a static uniform external environment and a low pulsar velocity. At 1.4–8.5 GHz, Dodson et al. (2003) have found that the Vela PWN has two bright patches bracketing the X-ray torus and jets in a structure quite similar to that in Figure 2 (right). Polarization imaging of the Vela radio structure suggests that these two patches represent the limbs of a toroidal $B$-field structure. This implies that the rotation axis controls the PWN symmetry to large radii.

2.3. Nebula Structure Fits

Following Ng & Romani (2004), we have fitted our new ACIS image to a point-source PSF, a Doppler-boosted equatorial torus, polar jets, and a uniform background. The fitting minimizes residuals using a Poisson-based likelihood function. Monte Carlo simulations of Poisson realizations of the best-fit model are in turn refitted to generate statistical errors and their covariance matrices. Table 1 contains the best-fit values. The torus radius and axis inclination and position angles are $r$, $\zeta$, and $\Psi$, respectively. See Ng & Romani (2004) for the definition of the other parameters and the details of the fitting technique. In Table 1 the inner jet and the counterjet are constrained to lie along the torus axis in the fits.

In addition to the statistical errors, there are certainly systematic errors, in particular those induced by unmodeled PWN components. For example, it is clear that there are counts in excess of the torus plus jet model in a cap surrounding the inner counterjet. Interestingly, similar structure is seen in the Crab PWN. We have made an attempt to constrain the systematic biases by modifying the fitting model. For example, allowing the (inner) jet and the counterjet to have a free position and amplitude shifts the best-fit position angle to $\Psi = 165^\circ \pm 0.5$ and the inclination to $\zeta = 56^\circ.7 \pm 1^0.0$. We therefore infer systematic errors that are about 3 times larger than our rather small statistical errors.

We have also measured the outer jet and counterjet system. If we minimize the residual to a one-dimensional line passing through the pulsar, the two jets together lie at $\Psi_{\text{outer}} = 169^\circ.4 \pm 0'.15$. If the jets are fitted separately, we obtain $\Psi_{\text{outer}} = 168^\circ.4 \pm 0'.2$ and $170^\circ.9 \pm 0'.2$ for the outer jet and counterjet, respectively. Thus, the two jets are misaligned at the ~8 $\sigma$ level. A fit to the count distribution about the best-fit axis shows that the narrow outer counterjet has a Gaussian FWHM across the jet of $2\theta^\circ 3 \pm 0'.2$. The outer jet appears broader at the base with an initial width of $4\theta^\circ 9 \pm 0'.5$, continuing at FWHM $= 2\theta^\circ 7 \pm 0'.3$ for its outer half. These estimates have been corrected for the telescope PSF, which is quite uniform this close to the aim point.

It is important to note that at the observation roll angle, the readout direction lies at $\Psi = 168^\circ.7$. Due consideration, however, shows that the jet structure cannot be produced by the readout trail. First, the jets cover only ~1; the readout excess should cover the full I3 chip. Second, the pulsar provides only ~2900 1–7 keV counts. The readout trail (out of time) image of this source should contribute only 36 counts over the full 8.3 strip across I3 and ~2.5 counts in the jet regions; the outer jet and counterjet have 92 and 93 1–7 keV counts, respectively. Finally, the outer jets are much harder than the soft X-ray emission from the pulsar; indeed, with a mean detected photon energy of ~2 keV, these are the hardest extended features in the image.

The overall system, showing an asymmetric torus, broad inner jets, and narrow outer jets is, of course, very similar to the Vela PWN as studied with Chandra by Pavlov et al. (2003). We discuss the comparison with the Vela system in § 3, highlighting the differences. We interpret these as suggesting that the PSR B1706–44 PWN has developed from a low-velocity pulsar.

2.4. Spectral Analysis

For the best possible constraints on the source spectrum, we have reprocessed both the ~11 ks cleaned ACIS-S data set and our new ~100 ks ACIS-I data set with the new time-dependent gain adjustment and CTI correction available in CIAO version 3.2. The updated response matrix files (RMFs) should in particular improve the low-energy calibration, important for obtaining the best estimates of $N_H$. As noted above, in these data sets the pile-up was negligible at ~3%. To model the aperture corrections, 10 PSFs with monochromatic energies from 0.5 to 9.5 keV were simulated using the Chandra Ray-Tracer program, ChaRT. The enclosed energy fraction as a function of radius was fitted to a linear function of energy, and this was used to correct the ancillary response files (ARFs) used in the spectral fit. In extracting the pulsar spectrum, an aperture of radius 1" was used to minimize nebular contamination. Results from the combined fits of the ACIS-I and ACIS-S pulsar data sets are listed in Table 1; the spectral fits are substantially better for composite models with both thermal and power-law components. Spectral parameter errors are projected multidimensional $1\sigma$ values. We quote both absorbed and unabsorbed fluxes. As is often the case with low-statistics X-ray spectra, projected (multidimensional) errors on the fluxes are very large due to spectral parameter uncertainties. Thus, we follow other authors in quoting flux errors as 1 $\sigma$ single-parameter values.

To get the best constraints on the point-source spectrum, Table 2 gives fits with $N_H$ held to the value from the power-law fits to the extended emission. We have also compared our results with the XMM-Newton fitting of McGowan et al. (2004) by fitting counts in the 20" aperture used in that observation. Our parameters and fluxes for the thermal component are generally in very good agreement. However, since this aperture contains much of the torus and central PWN, XMM-Newton substantially overestimates the nonthermal flux for the point source. Their fitted power-law flux corresponds to 7.5 x 10^{-12} ergs cm^{-2} s^{-1} (0.5–8 keV, unabsorbed). In the 20" aperture we find 9.6 x 10^{-13} ergs cm^{-2} s^{-1} (0.5–8 keV), while the small Chandra point-source aperture gives 2.3 x 10^{-13} ergs cm^{-2} s^{-1} (0.5–8 keV) for the power-law component. We find a similar factor of ~3 excess in the power-law plus atmosphere flux for the fit to the large XMM-Newton aperture. Conversion of the power-law flux observed in our small point-source aperture to the XMM-Newton band shows that the

| Parameter                | Value    |
|--------------------------|----------|
| $\Psi$ (deg)             | 163.6 ± 0.7 |
| $\zeta$ (deg)            | 53.3 ± 1.6  |
| $r$ (arcsec)             | 3.5 ± 0.08  |
| $\delta$                | 1.0 (fixed) |
| $\beta$                 | 0.70 ± 0.01 |
| Point source (counts)    | 2897 ± 23  |
| Torus (counts)           | 1221 ± 31  |
| Jet (counts)             | 185 ± 41   |
| Counterjet (counts)      | 325 ± 34   |

TABLE 1

Torus Fit Parameters with 1 $\sigma$ Statistical Errors
expected pn plus MOS (0.2–10 keV) count rate is 18% of the total (power law plus thermal) counts in the 20" source PSF in the subluminous zone at 2" pulsed. Extrapolation of the PWN count excess above the point-source fraction of 12%, some of the power-law counts must be unpulsed. We produce 21% of the hard-band flux, but this only has a pulse fraction of 12% (soft), 12% (hard), respectively. However, the light curves of McGowan et al. (2004) show that the pulse fractions are 21% (soft), 12% (hard), and 11% (total). Since the small-aperture power law produces only 12% of the soft counts but 21% are pulsed, there must be a thermal pulse component. Conversely, since the power law produces 21% of the hard-band flux, but this only has a pulse fraction of 12%, some of the power-law counts must be unpulsed. Extrapolation of the PWN count excess above the point-source PSF in the subluminous zone at 2" count produces 11% of the point-source aperture counts. Thus, the larger scale torus emission does not contribute significantly to the point-source power law and cannot account for its unpulsed component. This suggests that part of the magnetospheric emission is nearly isotropic or that there is a very compact (≤ 1") PWN component at the pulsar position.

For the thermal component, the fit flux gives an emitting area (effective radius) as a function of distance. Our fit to a pure blackbody gives $R_{\text{eff}} = 2.8 d_{1} \text{km}$. Thus, for reasons discussed above, this flux represents hot $T \gtrsim 2 \times 10^{6}$ K emission from a small fraction of the stellar surface (≈4.5% for a $R_{\infty} = 13.1 \text{ km star}$). The light-element neutron star atmosphere models, such as the pure H 10$^{12}$ G model grid used here (Zavlin et al. 1996), have large Wien excesses. When fitted, they give lower values of $T_{\text{eff}}$. Also, the blackbody departures allow one, in principle, to fit both the surface redshift and the radius. In practice, these are typically highly degenerate in CCD-quality data. We assume here a generic surface radius of $R_{\infty} = 10 \text{ km}$, corresponding to $R_{\infty} = R_{s}(1 - 2GM/R_{s}c^{2})^{-1/2} = 13.1 \text{ km}$. With $N_{H}$ free [giving $(5.9 \pm 0.9) \times 10^{21} \text{ cm}^{-2}$], our thermal flux normalization gives a radiating radius of $R_{\infty} = 27.4 d_{1} \text{ km}$, which is difficult to reconcile with expected neutron star radii for any $d > 1.8 \text{ kpc}$. However, when $N_{H}$ is fixed at the nebular value of $5 \times 10^{21} \text{ cm}^{-2}$, we get an effective radius of $R_{\infty} = 16.1 d_{1} \text{ km}$, which is tolerable even at our nominal 3 kpc distance.

Analysis of the low-S/N, extended flux depends critically on the background subtraction. Given the limited statistics, only simple absorbed power-law fits were attempted for all nonthermal sources. The results are listed in Table 3. For consistency, all fits are to the 0.5–8 keV range, and we quote both absorbed and unabsorbed fluxes.

Note that there is significant softening of the extended emission as one progresses to larger scales and that the jet components appear to be the hardest of all. This is certainly consistent with the idea that the central pulsar supplies fresh energetic electrons and that synchrotron burn-off increasingly softens the spectrum as older populations are viewed in the outer PWN. Again, this trend is common in the well-measured young PWNe. If we allow the photon index to vary for the different nebula components, the best fit to a global absorption value for the extended emission gives us our fiducial $N_{H} = 5 \times 10^{21} \text{ cm}^{-2}$. This is consistent with free-fit values for the point source, but given the complexities of the composite thermal plus power-law model, we consider the nebular fit value more robust. Note that with DM = 75.7 cm$^{-3}$ pc, the $N_{H}/n_{e} \approx 21$ for this sight line is large but not unprecedented for low-[$b$] pulsars. This is also consistent with the H I absorption measurements and a fiducial SNR distance of ~3 kpc, given the appreciable uncertainties.

### 3. Interpretation and Conclusions

A number of authors have discussed the evolution of a PWN within an expanding supernova remnant. For example, van der Swaluw et al. (2001) and Chevalier (2005) describe the early evolution...
evolution when the supernova ejecta are in free expansion. Later, after the remnant interior is heated by the passage of the reverse shock, the PWN evolves within the Sedov phase SNR whose radius is $R_{SNR} = 1.17(E_0/\rho)^{1/3} t_{74}^{2/3}$ for an explosion energy $E_0$ in a $\gamma = 5/3$ medium of density $\rho$. PSR B1706–44 has a characteristic age $10^4 t_4$ yr with $t_4 \approx 1.7$, so G343.1–2.3 should be safely in the Sedov phase, with an expected angular size of

$$\theta_{SNR} \approx 16'(E_{51}/n_0)^{1/5} t_4^{4/5}/d_3$$

(1)

for a supernova releasing energy $E_0 = 10^{51} E_{51}$ ergs in an external medium density of $n_0$ cm$^{-3}$, at a time $10^4 t_4$ yr ago and a distance of $3d_3$ kpc. The observed size then implies $E_{51} \approx 11n_0 t_4^{-2} d_3^2$, requiring a fairly energetic explosion for $d > 2$ kpc. During the Sedov phase the interior pressure is

$$P_{SNR} \approx 10^{-9} E_{51}^{2/5} n_0^{3/5} t_4^{-6/5}$$

(2)

and is relatively constant away from the SNR limb.

The pulsar blows a wind bubble within this SNR interior, whose radius is $R_{PWN} \approx (E_0/E_0)^{1/3} R_{SNR}$ for a PWN bubble energy of $E_0 = f E_{\pi}$ (van der Swaluw & Wu 2001). Although the accuracy of this dependence on PWN radius on pulsar injection energy has been questioned (Blondin et al. 2001), we adopt it for the following estimates. With the observed ratio of radii, $R_{PWN}/R_{SNR} = 11/257$, we obtain $E_0 = (3.7 \times 10^{-4}) E_0$; i.e., this PWN has quite low internal energy. This is also reflected in the low radio and X-ray fluxes. Together we use these estimates, the observed size of the SNR, equation (1), and the measured $E_{36} = 3.4$ and $t_{\pi} = 1.75 \times 10^4$ yr to write $t = (R_{PWN}/R_{SNR}) E_0/(E_{\pi}) = 2.11 n_0 t_4^{-6/5} d_3^2$. Now, if the PWN is adiabatic and we assume spin-down with constant $B$ and braking index $n = 3$ from an initial period $P_0$, we find that the total energy in the plerion is $[P/P_0]^{3/2} - 1$: setting $f = (P/P_0)^2 - 1$ and eliminating the true age $a$ using $t = t_\pi [1-(P_0/P)^2]$ for magnetic dipole spin-down, we obtain a constraint on the initial spin period of

$$[1 - (P_0/P)^3]^2 (P_0/P)^2 = 0.68 n_0 d_3^5,$$

(3)

which has a solution of $P_0 = 0.61 P = 62$ ms for $d = 3$ kpc and $P_0 = 0.79 P = 80$ ms for $d = 2$ kpc. The corresponding true ages are $0.61 t_\pi (1.1 \times 10^4$ yr) and $0.38 t_\pi (0.67 \times 10^4$ yr), respectively. These numerical values are for $n_0 = 1$, and the density dependence from equation (3) is quite weak. van der Swaluw & Wu (2001) present a similar sum for $P_0$ assuming a known $E_0$; the above formulation emphasizes the sensitivity to the poorly known $d$. Note that with the large implied initial period, the integrated PWN energy is quite comparable to the present spin energy, with $f \approx 1.7$ at $d = 3$ kpc and $f \approx 0.62$ at $d = 2$ kpc. So the spin-down luminosity is roughly constant in the adiabatic phase and the PWN growth is closer to $t^{1/2}$ than to the $t^{3/10}$ law appropriate for impulsive energy injection (van der Swaluw et al. 2001).

Inside this wind bubble, the Sedov interior pressure confines the PWN, giving rise to a termination shock at

$$\theta_{WS} \approx (E/4\pi c P_{SNR})^{1/2}/d,$$

(4)

which results in $\theta_{WS} \approx 1.7 E_{51}^{1/2} E_{0}^{1/2} n_0^{-3/10} t_4^{3/5} d_3^{-1}$. If we apply the SNR estimate for $E_0$ above, this becomes $\theta_{WS} \approx 0.72 E_{51}^{1/2} n_0^{-1/2} t_4 d_3^{-2}$. Then, by using $E_{36} \approx 4$ and applying the age estimate following equation (3), we get $\theta_{WS} \approx 1.5 n_0^{-1/2} (d = 3$ kpc) or $\theta_{WS} \approx 2.1 n_0^{-1/2} (d = 2$ kpc). These estimates are reasonably consistent with the observed $3''$ torus radius, especially since an equatorially concentrated flow should have a standoff distance of 1.5–2 times this spherical scale. The polar jets can have an initial shock at a somewhat larger angle, with the resulting pitch angle scattering illuminating the jets somewhat farther from the pulsar.

Of course, this bubble is offset from the center of G343.1–2.3 at $R = 0.5 R_{SNR}$ (Fig. 1). This is inside the $\sim 0.68 R_{SNR}$, where van der Swaluw et al. (2004) note that the increasing density causes the pulsar to be supersonic, so a bow should not have yet formed. These authors, however, compute numerical models of a fast-moving pulsar in a SNR interior. As the pulsar moves, the PWN should become highly asymmetric with a “relic PWN” at the SNR center and the pulsar placed near the leading edge of the PWN; see Figures 7 and 8 of van der Swaluw et al. (2004). We see no PWN structure near the geometric center of G343.1–2.3, and if the “bubble nebula” is identified with the shocked pulsar wind, the pulsar is certainly not offset from its center along the proper-motion axis (away from the SNR center). So these models are an inadequate description of G343.1–2.3. From Figure 2, the pulsar appears well centered in the bubble nebula, with any offset from its center along the axis to the SNR substantially less than $30 \Delta d_3$ arcsec. Thus,

$$v < 40 \Delta d_3 t_4$$

(5)

and the pulsar cannot have moved far from the explosion center. This is, of course, consistent with the scintillation results.

We can reconcile the symmetric PWN with the offset SNR shell if we assume that the pulsar progenitor exploded toward the edge of a quasipshperical cavity. One scenario (also posited by Gvaramadze [2002] and Bock & Gvaramadze [2002]) can associate the low-velocity pulsar with G343.1–2.3 to assume that the progenitor star had a stellar wind of mass-loss rate $M \leq 10^{-8} \dot{M}_o$ yr$^{-1}$ and wind speed $10^3 v_8$ cm s$^{-1}$ over $t \approx t_{76}$ yr, typical of the $\sim 10 \dot{M}_o$ stars that dominate the pulsar progenitors (Maeder 1981). This evacuates a stellar wind bubble of size

$$\theta_{SW} = 46'(M \dot{M}_o v_8^2/n_0)^{1/5} t_4^{3/5}/d_3.$$  

(6)

During the main-sequence lifetime, the star moving at $10 v_8$ km s$^{-1}$ travels $\sim (2'') r_7 v_8/d_3$, and so it can easily traverse its wind bubble. Thus, one can imagine an off-center supernova in a nearly symmetric stellar wind bubble of radius $\sim 2'':$ the supernova blast wave expands to fill the bubble, passing to the Sedov phase near its present radius. The supernova produces a neutron star with little or no kick, placing the pulsar near its present position. This has the added advantage of accommodating the rather large SNR size with a more modest energy of a few times $10^{51}$ ergs. The PWN energy and size estimates above would then be somewhat amended; this would require a careful numerical simulation.

For the reasons detailed in the introduction, it is not yet clear that PSR B1706–44 and G343.1–2.3 are associated. Thus, for completeness we can consider the case in which the shocked pulsar wind blows an adiabatic bubble in a static, low-$\dot{P}_{SNR}$ external medium (Castor et al. 1975). If we assume that the pulsar was born (sans SNR) or entered a confining region of the ISM $\sim 10^4$ yr ago and that since then it has been spinning down at the present energy-loss rate, we find that it will blow a bubble of angular size

$$\theta_{BN} \approx 0.76(E^3/\rho)^{1/5}/d \approx 120''(E_{36}/n_0)^{1/5} t_4^{3/5}/d_3.$$

(7)
These estimates change somewhat for a pulsar born at \( P_0 \ll P; \) since we are not making the association with the SNR G343.1–2.3, we can make no estimate of the initial spin period. As first noted by Dodson & Golap (2002), the ~4' wide radio spur across the face of G343.1–2.3 has the approximate scale of such a bubble nebula. If the PWN stays unmixed (relativistic), then the interior of the bubble will have a pressure \( P_{\text{BN}} \approx \frac{E \pi (4\pi R^3)}{6} \approx (1.6 \times 10^{-10}) \left( \frac{E}{10^{51}} \right)^{2/3} \text{erg cm}^{-2} \text{s}^{-2}. \) In turn, the torus termination shock in this medium is at

\[ \theta_{\text{WS}} \approx 2.9 \left( \frac{E_{36}}{n_0} \right)^{3/10} \left( \frac{r}{d} \right)^{2/5}. \]  

(8)

If (e.g., through Rayleigh-Taylor instabilities) the pulsar wind is well mixed with the swept-up gas, the adiabatic thermal pressure would be ~2 times larger. Interestingly, the angular scales for this scenario are also reasonably compatible with the observed torus and bubble nebula size. Of course, this scenario leaves open the question of the pulsar origin. Again, the pulsar would need to have a quite low velocity to produce the observed symmetry.

Turning to the spectral results, we note that Possenti et al. (2002) fitted a correlation between spin-down energy and the PSR plus PWN luminosity: \( L(2–10 \text{ keV}) = (1.8 \times 10^{48}) E_{40}^{1.3} \text{ ergs s}^{-1}. \) For the PSR B1706–44 parameters, this predicts a flux \( f(2–10 \text{ keV}) = (4.7 \times 10^{-12}) d_{10^3}^{-2} \text{ ergs cm}^{-2} \text{s}^{-1}. \) The observed 2–10 keV flux is in fact ~1.7 \times 10^{-12} ergs cm^{-2} s^{-1}, even including the outer bubble nebula; without this component it is half as large. These correlations are not very accurate, but this does imply that the PSR B1706–44 PWN is substantially underluminous for any distance less than 3 kpc. Gotthelf (2003) has derived correlations between the pulsar spin-down power and the pulsar and PWN spectral indices. His relation predicts \( \Gamma_{\text{PSR}} = 0.63 \pm 0.17 \) (substantially smaller than our power-law index of \( \sim 1.6 \pm 0.2 \)) and \( \Gamma_{\text{PWN}} = 1.3 \pm 0.3 \) (not inconsistent with the values measured for the torus and equatorial PWN).

As described in § 2.4, the spectrum softens appreciably from the central torus to the outer bubble nebula. This suggests increased aging of the synchrotron population. Figures 2 and 3 show that the bulk of the radio emission lies in the bubble nebula region. So we can take the radio flux and spectral index from Giacani et al. (2001) and compare with our nebula X-ray flux (Fig. 4). Comparing the radio spectral index \( \alpha_R = 0.3 \) with the best-fit X-ray index \( \alpha_X = 0.77 \) shows a break quite close to the \( \Delta \alpha = 0.5 \) expected from synchrotron cooling. The extrapolated intersection of these power laws gives a break frequency of \( \nu_b = 12.2 \pm 0.9 \text{ MHz}. \) For the fiducial pulsar age of ~1.7 \times 10^4 yr, this corresponds to a nebula field of \( 1.4^{+2.1}_{-0.6} \times 10^{-4} \text{ G}. \) Note that the magnetic pressure from this (photon flux weighted) average flux is \( 8 \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1}, \) somewhat larger than the nebula pressure estimated from its radius. This may indicate field compression in the nebula limb. In general, if the mean nebula field is \( 10^{-4} B_{-4} \text{ G} \) for a nebula of angular radius \( \sim 1000\theta_{100} \text{pc}, \) the total nebula field energy is \( E_{B} \approx (1.5 \times 10^{47}) B_{-4}^2 \theta_{100} d_{10}^3 \text{ ergs}. \) This is comfortably less than the present spin energy of \( E_{\text{PSR}} \approx 2 \times 10^{48} \text{ ergs}, \) so the nebula can be easily powered even if the pulsar was born close to its present spin period. We find that this cooling break field is substantially larger than the equipartition field of \( 10–15 \mu \text{G} \) inferred for the radio- and X-ray-emitting populations (also, the minimum equipartition nebula energy of \( \sim 9 \times 10^{45} \text{ ergs} \) is substantially smaller). The cooling break field can also be compared to that expected from simple radial evolution of the pulsar surface field: if this field \( B_s = 3 \times 10^{12} \text{ G} \) falls off as \( r^{-3} \) to the light cylinder and then as \( 1/r \) to the wind shock where it is compressed, we get \( B_{\text{WS}} \sim 3B_s r_s^3/(r_{\text{WS}}^2) \sim 1 \text{ mG}. \) If it continues to fall off as \( 1/r \) beyond this, we get a field at the limb of the bubble nebula of \( \sim 30 \mu \text{G}. \) So the best we can do is to infer a mean nebular field of ~10–30 times the equipartition value, with some generation of new field beyond the torus wind shock. The energetic requirements for this field, required to match the \( \nu_B \) cooling break, are comfortably less than the energy available from PSR B1706–44. These field estimates are consistent with the nondetection of TeV inverse Compton scattering (ICS) flux from this source (Aharonian et al. 2005).

The narrow outer jets also have a power-law spectrum and are almost certainly synchrotron-emitting. For a reasonable \( 0.1 B_{-4} \text{ mG} \) field, the observed X-rays of \( E_x = 1.5B_{-4}E_{x} \text{ keV} \) require substantial \( e^-e^+ \) energies, with \( \Gamma_x = (3 \times 10^4)^{1/3} \text{ near the radiation-reaction–limited primary Lorentz factor inferred for many polar cap (Muslimov & Harding 2003) and outer magnetosphere (Romani 1996) pulsar models. Since the jet is narrow, confinement of these pairs imposes a (not very restrictive) lower bound on the jet field of \( B_{-4} > 0.075E_{x}^{1/3}/(d_{10} \theta_{10}^2) \text{ where the observed jet photon has } E_x \sim 5E_{x} \text{ keV and the observed outer jet half-width is } \theta_{10} \text{ in arcseconds}. \) A more restrictive upper limit on the mean jet field comes from the observation that the jets do not soften noticeably before their end at ~30\( \theta_{10} \) arcsec from the pulsar. If we assume a jet bulk speed \( \beta c \), then arguing that the flow time is shorter than the synchrotron cooling time gives us the limit \( B_{-4} < 8.5 \beta^2(d_{10} \theta_{10}^2)^{1/3}/E_{x}^{5/3}. \) When the observed jet spectrum has an energy index of \( \alpha = \Gamma - 1 \approx 0.3, \) we infer a power-law spectrum of \( e^-e^+ \) in the jet \( N(\Gamma_x)d\Gamma_x = K \Gamma_x^{-\alpha}d\Gamma_x, \) with \( p = 2\alpha + 1 \approx 1.6. \) We can then make an estimate of the minimum jet luminosity, i.e., at “equipartition,” when \( B^2 = 6\pi m_e c^2 \int \Gamma_x N(\Gamma_x) d\Gamma_x. \) Given the observed combined outer jet luminosity (0.5–8 keV) of \( L = 4\pi d^2f_{\omega} \approx 2.7 \times 10^{31} \text{ ergs s}^{-1}, \) and the emitting volume of \( V = 2\theta_{10}^2\pi \theta_{10} d_{10}^2 \approx (1.1 \times 10^{52})(\theta_{10}/20)^2 \text{ cm}^3, \) with the angles in
arcsseconds, we can estimate the equipartition field for an isotropic plasma as

$$B_{eq} = \left[ \frac{18\pi}{\sigma} \left( \frac{2\pi m_e c}{E_{max}} \right)^{2} \frac{2(1 - \alpha)}{1 - 2\alpha} \frac{1}{V} \right]^{2/7} L^{2/7},$$

where the observed photon spectrum runs from $E_{min}$ to $E_{max}$. For the observed flux, this gives

$$B_{eq} \approx (0.25 \times 10^{-4}) q(\alpha) (\theta_{ej} d_{3}/20)^{-2/7} G,$$

where $q(\alpha) = 0.3 = 1$ is a weak function of $\alpha$. The corresponding minimum energy flux for the outer jet is

$$L_{ej} = (8 \times 10^{33}) \beta c d_{3}^{12/7} \theta_{ej}^{10/7} \omega_0^{10/7} d_{1}^{-2/7},$$

where the jet bulk velocity is $\beta c$. This is $\sim 10^{-3} E$ per jet and will, of course, be larger if the jet flow includes ions. Interestingly, if the pulsar couples roughly isotropically to the PWN, then the corresponding fraction of the outflow should subtend a half-angle of $\sim 5^\circ$. This is somewhat smaller than the angle subtended by the inner jets but $\sim 3$ times larger than the $\sim 1^\circ$ width of the ends of the jet—there is substantial collimation of the jet energy flux.

We have argued that a low PSR velocity can explain the symmetry of the PWN. The central location of the pulsar and spherical postshock flow may also allow the equatorial toroidal structure and polar jets to propagate undisturbed to large radii. We do, however, measure a small misalignment of the outer jets, corresponding to a deflection of $\theta_{de} = 1^\circ.3 \pm 0.15$ for each. If we imagine a pressure acting along the jet’s $\sim 30^\circ$ length, then the required perturbation is $\delta P \approx L_{ej} \tan \theta_{de} / (\beta c A_{0}) \approx (5 \times 10^{10}) L_{34} (\beta d_{3} \theta_{ej} d_{1}^{2}) g \text{ cm}^{-1} \text{ s}^{-2}$, where $A_{0}$ is the jet’s cross-sectional area. This is only $10^{-3}$ of the total pressure in the nebula. It could be due to ram pressure if the shocked nebular medium flows to the west at $\sim 1.7 \text{ km s}^{-1}$.

Our X-ray measurements have established the PWN symmetry axis, presumably reflecting the pulsar spin axis, to very high precision. Unfortunately, our original goal of relating this to the proper-motion axis remains unfulfilled. It is true that the torus symmetry axis points roughly toward the center of G343.1–2.3, confirming the estimates from earlier Chandra data. However, the PWN symmetry about the pulsar and the low scintillation velocity suggest a very low transverse speed of $\leq 40 \text{ km s}^{-1}$, which would preclude a birth site as distant as the SNR center. This low speed makes a direct proper-motion measurement challenging, but it allows latitudinal asymmetries in the PWN flow to propagate undisturbed to fairly large radius, where they can be imaged with Chandra. Thus, study of this PWN offers some good opportunities to probe outflow dynamics and jet collimation. Study of this and similar PWNe may prove useful.

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