YOUNG ENERGETIC PSR J1617–5055, ITS NEBULA, AND TEV SOURCE HESS J1616–508

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ABSTRACT

We observed the young pulsar J1617–5055 with the Chandra ACIS detector for 60 ks. In addition to the pulsar, the X-ray images show a faint pulsar wind nebula (PWN) seen up to ∼1′ from the pulsar. Deconvolution and reconstruction of the image reveal a brighter compact PWN component of ∼1′ size. The total PWN luminosity in the 0.5–8 keV band, \( L_{\text{pwn}} = (3.2–3.7) \times 10^{33} \text{ erg s}^{-1} \) for \( d = 6.5 \text{ kpc} \), is a fraction of 2 × 10−3 of the pulsar’s spin-down power \( \dot{E} \) and a fraction of 0.2 of the pulsar’s X-ray luminosity, which is a factor of 20 lower than one would expect from an average empirical relation, \( L_{\text{pwn}} \sim 4L_{\text{psr}} \). The pulsar’s spectrum can be described by an absorbed power law with \( n_H \approx 3.5 \times 10^{22} \text{ cm}^{-2} \) and \( \Gamma \approx 1.1 \), harder than any other pulsar spectrum reliably measured in the soft X-ray band. This nonthermal emission is \( \approx 50\% \) pulsed, with one peak per period.

We have also investigated a possible connection between J1617 and the extended TeV source HESS J1616–508 whose center is located 10′ west of the pulsar. We find no preferential extension of the X-ray PWN toward the TeV source. Therefore, the Chandra data do not provide conclusive evidence for PSR J1617–5055 and HESS J1616–508 association. We have also analyzed archival X-ray, radio, and IR data on the HESS J1616–508 region and found traces of diffuse emission coinciding with the central part of HESS J1616–508. We speculate that the TeV source may be multiple, with most of the emission coming from an unknown supernova remnant or a star forming region, while some fraction of the TeV emission still may be attributed to the PWN around PSR J1617–5055.

Key words: ISM: individual (HESS J1616–508) – pulsars: individual (PSR J1617–5055) – stars: neutron – X-rays: ISM

Online-only material: color figure

1. INTRODUCTION

High-resolution X-ray observations of young (\( \tau \lesssim 10 \text{ kyr} \)) rotation powered pulsars usually show a pointlike pulsar embedded in a pulsar wind nebula (PWN). In most cases, the pulsar emission is dominated by the nonthermal emission generated in the pulsar magnetosphere. The X-ray spectrum of this emission usually fits a power-law (PL) model with typical photon indices \( \Gamma \approx 1–2 \). As a rule, the nonthermal emission component is strongly pulsed, showing one or more peaks per period. Studying the nonthermal emission constrains the emission and particle acceleration mechanisms in the pulsar magnetosphere. Young pulsars are also interesting because they emit strong magnetized relativistic winds which interact with the ambient medium and form PWNe whose emission is interpreted as synchrotron radiation from the shocked pulsar wind (see Kaspi et al. 2006; Gaensler & Slane 2006; Kargaltsev & Pavlov 2008, hereafter KP08, for reviews). Studying PWNe helps one to understand the structure and dynamics of relativistic pulsar winds; elucidate the mechanisms of PWN formation, evolution, and interaction with the ambient medium, and establish the properties of the relativistic plasma in PWNe.

The young (\( \tau \equiv P / 2 \dot{P} = 8.13 \text{ kyr} \); \( \dot{E} = 1.6 \times 10^{37} \text{ erg s}^{-1} \)) 69 ms pulsar J1617–5055 (hereafter J1617) was first identified through its X-ray pulsations with ASCA (Torii et al. 1998) with the radio pulsations found shortly afterward (Kaspi et al. 1998). The ASCA spectrum of the pulsar was described by the absorbed PL model with the photon index \( \Gamma = 1.4 \pm 0.2 \) and the observed flux \( F_X = (3.6 \pm 0.2) \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) in the 3–10 keV band (Torii et al. 2000).

Since the ASCA detection, J1617 has been observed with other X-ray satellites. It was imaged 6′ off-axis in Chandra ACIS observations of the RCW 103 supernova remnant (SNR) in 1999 September (Garmire et al. 1999) and 2000 February. It was also observed by XMM-Newton in 2001 September (two pointings, 30 ks aimed at the pulsar, and 20 ks centered at RCW 103). The J1617 properties inferred from these XMM-Newton observations have been briefly reported by Becker & Aschenbach (2002; hereafter BA02). They found that the spectrum in the 0.5–10 keV band fits the absorbed PL model with \( \Gamma = 1.1–1.4 \), \( n_H = (2.8–3.6) \times 10^{22} \text{ cm}^{-2} \), and unabsorbed flux \( F_X^{\text{abs}} = (4.9–5.4) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \) (the numbers correspond to the 90% confidence range). BA02 also have identified pulsations with a single, asymmetric pulse and a pulsed fraction of ∼50% in the 2.5–15 keV band. These observations confirmed the nonthermal nature of the pulsar emission; however, they lacked the resolution needed to separate the pulsar emission from the emission of a possible compact PWN around this young, remote (\( d \approx 6.5 \text{ kpc} \)) pulsar. J1617 was also observed serendipitously by XMM-Newton in 2005 August (11′ off-axis, ∼ 90 ks exposure).

J1617 has been also detected at higher energies with RXTE PCA and HEXTE (2–60 keV band; Torii et al. 2000; Kuiper 2007), and Integral IBIS/ISGRI (20–300 keV band; Landi et al. 2007). Landi et al. (2007) have produced a joined spectral fit to the XMM-Newton, BeppoSAX, and Integral data and found fitting parameters close to those obtained by BA02 from the XMM-Newton data alone (\( \Gamma = 1.4 \pm 0.1 \), \( n_H = (3.9 \pm 0.3) \times 10^{22} \text{ cm}^{-2} \)).

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3 The 69 ms pulsations from this region were first detected with Ginga (Aoki et al. 1992), but it was impossible to determine the source of these pulsations because of the very poor angular resolution of Ginga.
and $F_{\text{unabs}} = 4.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in 2–10 keV). Fitting the RXTE spectrum in the 2–30 keV band with a PL model, Kuiper (2007) found $\Gamma = 1.30 \pm 0.01$ for fixed $n_H = 3.2 \times 10^{22}$ cm$^{-2}$.

Observations of J1617 and its surroundings have become particularly interesting after the discovery of the extended (∼20′ in diameter) TeV source HESS J1616–508 (hereafter HESS J1616) by Aharonian et al. (2006). Although its center of gravity is offset by ∼10′–11′ from the pulsar, the extent of the TeV emission still encompasses the pulsar location. The HESS J1616 spectrum above 200 GeV fits a PL model with $\Gamma = 2.35 \pm 0.06$ and 1–10 TeV flux $F_{\text{TeV}} \approx 1.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The central region of HESS J1616 was observed with Suzaku XIS, but no X-ray counterpart was found to a limiting flux of 3.1 × 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$, so that the TeV source was suggested to be “the best example in the Galaxy of a dark particle accelerator” (Matsumoto et al. 2007). Landi et al. (2007) observed the field of HESS J1616 with Integral IBIS/ISGRI and Swift XRT, and also analyzed archival XMM-Newton and BeppoSAX data. These authors concluded that J1617 is the only plausible counterpart to the TeV source.

For many young pulsars, radio or X-ray SNR associations have been found, but no SNR association has been established for J1617 so far. Although J1617 is just ∼7′ north of the center of the RCW 103 SNR, outside the 5′ SNR radius, the pulsar is almost certainly unrelated to the SNR. RCW 103 hosts a central compact object (CCO; possibly an NS binary or a transient magnetar; e.g., Pavlov et al. 2002, 2004; de Luca et al. 2007), which is a more plausible candidate for the compact remnant of the SN explosion. In addition, the RCW 103 spectrum shows a significantly smaller interstellar absorption than J1617 (Gotthelf et al. 1997). The relative positions and sizes of HESS J1616 and RCW 103 suggest that the HESS source is also not associated with the SNR.

To search for a compact X-ray PWN around J1617 and separate the pulsar and PWN emission, we have carried out a deep Chandra ACIS observation of J1617 in 2006 June, with the pulsar located near the optical axis. Some results of this observation have been reported by Pavlov et al. (2008) and Chang et al. (2008). Here we present the detailed analysis of this observation and our analysis of archival multiwavelength data on J1617 and HESS J1616. In Section 2 we describe the observations, the images of the J1617 PWN and the HESS J1616 field, and the spectral analysis of the pulsar and the PWN. We discuss the pulsar and PWN properties and the nature of HESS J1616 in Section 3, and summarize our findings in Section 4.

### 2. OBSERVATIONS AND DATA ANALYSIS

We observed J1617 with the Chandra ACIS detector on 2006 June 6 (ObsID 6684) for 60 ks in timed exposure (TE) mode with very faint (VF) telemetry format. The pulsar was imaged on the ACIS-I3 chip near the optical axis. The other ACIS chips were turned off. To reduce the pile-up in the pulsar image, we used 1/4 subarray (∼8′ × 2′ field of view (FOV); frame time 0.84104 s, including 0.8 s exposure time and 0.04104 s “dead time”). No substantial background changes were detected during the entire observation. The scientific exposure time was 57.24 ks. We will also use in this work two archival Chandra ACIS imaging observations of 1999 September 26 (ObsID 123) and 2000 February 8 (ObsID 970). As the primary target of those observations was the RCW 103 SNR, the pulsar was imaged ∼6′ off-axis, which resulted in a broadened point-spread function (PSF). The frame time was 3.24104 s in both observations (other details are given in Table 1). The second observation suffered from significant background flares (up to six times the quiescent level). Filtering out the flares reduced the exposure by ≈5 ks.

In addition we analyzed the ACIS observation of 2002 March 3 (ObsID 2759). The data were taken in continuous clocking (CC) mode, which allows one to achieve a time resolution of 2.85 ms at the expense of spatial information in one dimension.

The central part of HESS 1616 was serendipitously imaged on the ACIS S2 and S3 chips during the Chandra observations of the Kes 32 SNR that occurred on 2001 October 10 (ObsID 1960). The data were taken in faint mode, and the scientific exposure time was 29 ks (Vink 2004). Reduction of the Chandra data was done with the Chandra Interactive Analysis Observations (CIAO) software (ver. 3.4, 4.0; CALDB ver. 3.3.0.1, 3.4.0) and FTOOLS (ver. 6.3). In our image analysis we have made use of MARX$^4$ and Chandra Ray Tracer (ChaRT) software.$^5$ We also used XSPEC (ver. 11.3.2) for the spectral analysis.

J1617 was observed on-axis with the XMM-Newton EPIC MOS1 and MOS2 detectors on 2001 September 9 (ObsID 0113050701).$^6$ It was also serendipitously observed ∼11′ off-axis with the same detectors during the observation of RCW 103 on 2005 August 23 and 24 (ObsID 0302390101). In both observations the two MOS cameras were operated in full window mode (2.6 s time resolution) with the medium optical filter; the dead-time-corrected exposure times were 27.8 ks and 86.3 ks, respectively. During the 2001 observation, the EPIC PN camera was in timing mode, while it was in small window mode, with J1617 outside the FOV, during the 2005 observation. For the XMM-Newton data analysis, we used the Processing Pipeline Subsystem (PPS). Both the 2001 and 2005 observations were strongly contaminated by flares during which the background count rate exceeded the quiescent level by a factor of up to 16. Filtering the flares out left 22.2 ks and 70.3 ks useful scientific exposure for the first and second observations, respectively.

#### 2.1. PWN and Pulsar Images

Figure 1 shows binned and smoothed large-scale images of J1617 and its surroundings in the 2–8 keV band. The upper panel shows the 1/4 subarray ACIS-I3 image from our observation of 2006 June. In this image we see a relatively bright pointlike source at the radio pulsar position embedded in faint diffuse emission extended more toward the south and southeast of the pulsar. The asymmetry is better seen in the ACIS images from earlier observations (Figure 1, middle and bottom), which have larger FOVs, with the pulsar ∼3′ north of the RCW 103 shell seen near the bottom in each of the two images.

Figure 2 shows a close-up view of J1617 and its immediate vicinity from our observation of 2006 June. With the pulsar imaged on-axis, this observation provides a much better resolution than the off-axis ACIS observations of 1999 and 2000. The pointlike source, surrounded by diffuse emission, is centered at R.A. = 16$^h$17$^m$29.35 s, decl. = −50°55′12′′ (J2000).

$^4$ The Model of AXAF Response to X-rays (MARX) is a suite of programs designed to enable the user to simulate the on-orbit performance of the Chandra satellite. See http://space.mit.edu/ASC/MARX/.

$^5$ The software is available at http://cxc.harvard.edu/chart/.

$^6$ J1617 was also serendipitously imaged off-axis in the observation 0113050601 on the same date. We do not analyze this observation because a much longer XMM-Newton observation of 2005 August is available, with about the same pointing and roll angle.
Table 1  

| Obs. ID | Date       | Mode, chip region | Telemetry format | Chips activated | J1617 imaged on | Off-axis angle | Sci. Exp. (ks) | Notes |
|---------|------------|-------------------|------------------|----------------|----------------|----------------|---------------|-------|
| 123     | 1999 Sep 26| TE, full frame    | VF               | I0-I3,S2,S3    | I1             | 6.1            | 13.92         |       |
| 970     | 2000 Feb 8 | TE, full frame    | F                | I2,I3,S2-S4    | I3             | 6.1            | 13.75         |       |
| 2759    | 2002 Mar 3 | CC, full frame    | F                | I2,I3,S1-S4    | I3             | 6.3            | 48.82         |       |
| 6684    | 2006 Jun 6 | TE, 1/4 subarray  | VF               | I3             | I3             | 40‘            | 57.24         |       |

Notes. Except for Obs. ID 970, the scientific exposures coincide with the live times given in the EVT2 file headers (for the chip of interest). In Obs. ID 970, removing the flares reduced this time by ≈ 5 ks.

Figure 1. *Chandra* images of the field around J1617 (see Table 1 for details). The bottom panel shows the combined image from 1999 and 2000 observations. All the images are binned to a pixel size of 4″ and then smoothed with the $r = 12″$ Gaussian kernel. The contrast is chosen to emphasize the faint large-scale emission. The extended shell, partly seen in the middle and bottom images, belongs to RCW 103.

The position uncertainty is dominated by the uncertainty in the *Chandra* absolute astrometry, 0′.65 at the 90% confidence level for sources within 2′ from the optical axis on the ACIS-I3 chip.7 As this position differs by only 0′.62 from the radio position of J1617 reported by Kaspi et al. (1998), the pointlike source must be the X-ray counterpart of the radio pulsar. The amorphous diffuse emission around J1617 is distinguishable from the background up to ≈ 1′ from the pulsar. The background-subtracted surface brightness of this extended PWN is $\approx 0.002 – 0.01$ counts arcsec$^{-2}$ ks$^{-1}$, being somewhat brighter south and southwest of the pulsar.

The radial profile of the detected emission, centered on the pulsar position, is shown in Figure 3 together with the simulated PSF and background level. We see that the extended, faint PWN prevails over the pulsar emission at distances $\approx 5′′$ from the pulsar.

Given the large distance to the pulsar and the faintness of the extended PWN, one could expect a more compact PWN component, which would not be immediately seen in pipeline-processed data. To search for such a component, we produced images of the immediate pulsar vicinity at subpixel resolution (see Figure 4). We first removed the pipeline pixel randomization and applied the subpixel resolution tool to split-pixel events in the image (Tsunemi et al. 2001; Morie et al. 2001). We then simulated the PSF image in the 2–8 keV energy band at the same position on the detector as in the real observation.

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7 See Section 5.4 and Figure 5.1 of the *Chandra* Proposers’ Observatory Guide ver. 10 at http://asc.harvard.edu/proposer/POG.

8 To simulate the PSF with ChaRT and MARX, we followed the steps outlined in http://cxc.harvard.edu/chart/threads/index.html. We have also tried several values of the Dither Blur parameter (see http://cxc.harvard.edu/chart/caveats.html and Misanovic et al. (2008) for discussion) and adopted the value of 0″.1 that provides the best match between the simulated PSF and the real data within $r \lesssim 3″$ from the pulsar.
similar features are often seen in Chandra images of PWNe around young pulsars (see e.g., KP08). The radial profile shown in Figure 3 (bottom) demonstrates the significance of the count excess at $r \approx 0'5 - 1'5$ from the pulsar.

For comparison, we also show a deconvolved ACIS image without removing the pipeline pixel randomization (Figure 4(e)). Although the deconvolution of this image does not recover as much structure as the images with the pixel randomization removed, it does show some of the features that are seen in the deconvolved nonrandomized images.

To test the reliability of the deconvolution procedure, we applied it to the ACIS image of the CCO in the Cas A SNR (ObsID 6690), a radio-silent NS showing no radio pulsar activity, for which no PWN is expected (e.g., Pavlov et al. 2004). The ACIS image of the CCO has $\approx 7200$ counts within the $0'98$ radius around the source, comparable to J1617 in our ACIS-I image ($\approx 4700$ counts in the same aperture). Unlike J1617, the deconvolved image of the Cas A CCO preserves the point-like appearance with no extended structure (see Figure 4(f)). Although, as any deconvolution algorithm, arestore could introduce artifacts in the images, the test example of the Cas A CCO adds credibility to the features seen in the deconvolved images of J1617 (at least it demonstrates that the J1617 source is extended rather than pointlike).

2.2. The Field of HESS J1616–508

Since J1617 is considered as a plausible counterpart for the extended TeV source HESS J1616 (Landi et al. 2007), we have searched for additional data in the Chandra and XMM-Newton archives which would provide at least partial coverage of the HESS J1616 extent and allow us to look for other potential X-ray counterparts of the TeV source and examine its connection to J1617. In the Chandra archive we found an ACIS observation of the Kes 32 SNR (Vink 2004). During that observation, the S2 and S3 chips imaged the central part of HESS J1616 (see Figure 5(a)). The brightest source (marked X in Figure 5(a)) is located on the S2 chip around R.A. $\approx 16^h16^m10^s$, decl. $\approx -50^\circ54'30''$. Because of the small number of counts (140$\pm20$ counts within an $r = 40''$ circle in 0.5–8 keV, signal-to-noise ratio $(S/N) \approx 7$) and the broad PSF (FWHM $\approx 15''$ at the off-axis angle $\theta \approx 16'$), it is difficult to determine whether the source is extended or multiple; however, with the linear extent of $\approx 1'$, it does not appear to be pointlike. Assuming an absorbed PL spectrum with $\Gamma = 1.5$ and $n_{H,22} = n_{H}/10^{22}$ cm$^{-2} = 3.45$ (as found from the fit to the pulsar spectrum; see Section 2.3.1), the unabsorbed 0.5–8 keV flux of source X can be estimated as $F_X \sim (1.7–2.2) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

We see some hints of extended emission southwest of source X; however, the low count rate, $\sim 1.4$ counts ks$^{-1}$ arcmin$^{-2}$ in 0.5–8 keV (corresponding to the unabsorbed surface brightness of $\sim 6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ for the PL model with $\Gamma = 1.5$ and $n_{H,22} = 3.45$), precludes any detailed analysis of this diffuse emission.

Source X falls near the edge of the EPIC FOV in the 2001 observation (Figure 5(b)). Although some emission at the source X position is discernible, it is not possible to determine whether the source is extended or pointlike. Its brightest part in the EPIC image is shifted by about $30''$ southwest from the Chandra position (the difference could result from a statistical noise and background fluctuations).

Source X was outside the EPIC FOV in the 2005 XMM-Newton observation. Because of the low surface brightness...
and large XIS PSF, the source is not seen in the Suzaku data. Deeper ACIS or EPIC observations, with the center of the TeV source imaged close to the optical axis, are required to understand the nature of the detected extended X-ray emission.

In addition to analyzing the X-ray images, we examined the available IR and radio data on the region of interest. The 843 MHz image (Figure 5(d)) from the Sydney University Molonglo Sky Survey (SUMSS⁹) shows some diffuse emission surrounding the very central part of HESS J1616 (within the region of sky corresponding to the innermost TeV contour shown in Figures 5(a) and 5(f)). The radio emission looks like a patchy, elongated shell (shown by the dashed ellipse in Figure 5(d)), possibly an unknown SNR (alternatively, it could be several faint point sources accidentally aligned in a shell-like structure). The Spitzer IRAC images¹⁰ of the same region (Figures 5(e) and 5(f)) also reveal diffuse emission partly coincident with the radio emission. In addition, there are several compact sources seen in the radio and, especially, IR images within the central part of the TeV source. The brightest source, marked A in Figure 5, is located near the TeV source center. At 8 μm, source A is resolved into a complex shell with an additional lobe to the west and a number of compact point sources suggesting a star forming region. Source X appears to have IR counterpart(s) resolved into several compact diffuse sources at 8 μm (Figure 5(e)), possibly also star forming regions. Deeper radio observations with higher spatial resolution would be most helpful in understanding the nature of these sources.

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⁹ Bock et al. (1999); see also http://www.physics.usyd.edu.au/ioa/Main/SUMSS.
¹⁰ From Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003); see also http://irsa.ipac.caltech.edu/data/SPITZER/GLIMPSE/.

2.3. Pulsar Timing

The data from the CC mode observation of the RCW 103 CCO also allow one to analyze the pulsations of the J1617 pulsar since the pulsar falls within the FOV. The pulsar is clearly seen in the one-dimensional image shown in Figure 6; however, the large off-axis angle (≈ 6°) significantly broadens the PSF, making it impossible to separate the inner PWN and the pulsar.

For the timing analysis, we extracted 4057 photons in the 2–8 keV band from the 10′ wide segment centered on J1617 (shown in Figure 6, top; ≈ 90% of these counts are expected to come from the unresolved source, i.e., the pulsar and the compact inner PWN). The photon arrival times have been transformed to the solar system barycenter using the axBary tool of CIAO 3.4. We have searched for the pulsed signal near the expected radio pulsation frequency and found $Z^2_{\text{max}} = 301$ (see Buccheri et al. (1983) for details on $Z^2_n$ statistics) at $\nu = 14.414, 488 \pm 1 \mu$Hz, consistent with the frequency expected from the radio ephemeris (Kaspi et al. 1998) at the epoch of the Chandra observation. The light curve folded at this frequency reveals a single pulse with a flat minimum (see Figure 6, bottom). The observed 2–8 keV pulsed fraction (the ratio of the number of counts above the minimum level to the total number of counts) is 40% ± 4%. Correcting it for the background contribution (which includes the outer PWN), we obtain 44%±4%. The pulse profiles extracted in narrower energy bands (2–4 and 4–8 keV) are similar to the 2–8 keV pulse profile, both in shape and pulsed fraction. The small number of counts precludes a reliable measurement of the pulsed fraction below 2 keV.
2.4. Spectral Analysis

2.4.1. Pulsar

For our 1/4 subarray observation (ObsID 6684), we extracted the pulsar’s spectrum (using the CIAO’s psextract task) from a small circular aperture of $r = 0.5'$ to minimize the contamination from the compact PWN (see Figure 3, bottom, and also Figures 4(a) and 4(d)). No background subtraction was attempted because the PWN contribution is expected to be negligible in this small aperture (Figure 3, bottom). The 2853 counts extracted from the 0.5 radius aperture (52% encircled energy fraction) in the 1–8 keV range (there are virtually no counts below 1 keV) correspond to the aperture-corrected source count rate of $96 \pm 2$ counts ks$^{-1}$. The corresponding (aperture-corrected) absorbed flux is $F_{\text{psr}} \approx (2.2 \pm 0.1) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. With the (exposure) frame time of 0.8 s, the expected pile-up fraction is very small ($\approx 3\%$ according to PIMMS\textsuperscript{12}).

We binned the spectrum with minimum of 50 counts per bin and fit the absorbed PL model in the 1–8 keV range with all the fitting parameters allowed to vary. The quality of the fit is excellent ($\chi^2_\nu = 1.04$ for 49 degrees of freedom; see Figure 7). The hydrogen column density, $n_{\text{H,22}} = 3.45 \pm 0.14$ (see Figure 8; the errors here and below are at the 68% confidence level for a single interesting parameter) is a factor of 1.5 larger than the average Galactic H\textsc{i} column density in the direction of the pulsar ($l = 332.50^\circ, b = -0.28^\circ$), $n_{\text{H,21}} = 2.26$ (Dickey & Lockman 1990). This is not surprising since the $n_{\text{H}}$ deduced from an X-ray spectrum under the assumption of standard element abundances generally exceeds the $n_{\text{H,21}}$ measured from 21 cm observations by a factor of 1.5–3 (e.g., Baumgartner & Mushotzky 2006). The same PL fit gives the photon index $\Gamma_{\text{psr}} = 1.14 \pm 0.06$ and the unabsorbed flux $F_{\text{psr,unabs}} = (3.6 \pm 0.1) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$

\textsuperscript{11} Here and below we calculate the flux in a given aperture and energy range as $F = T_{\text{exp}}^{-1} \sum_{k=1}^{N} E_k A_k$, where $T_{\text{exp}}$ is the exposure time, $N$ is the number of counts, $E_k$ is the photon energy corresponding to the $k$th event, and $A_k = A(E_k)$ is the effective area for the photon energy $E_k$. The flux defined in this way does not depend on the spectral model, contrary to the flux provided by XSPEC after fitting with a spectral model.

\textsuperscript{12} http://cxc.harvard.edu/toolkit/pimms.jsp.
in the 0.5–8.0 keV band. It corresponds to the isotropic luminosity $L_{psr} \approx 1.8 \times 10^{34} d_{6.5}^2$ erg s$^{-1}$ ($=1.1 \times 10^{-3} d_{6.5}^2 E$).

13 We should note that this fit does not account for the energy dependence of the PSF. Because the PSF becomes narrower at lower energies, the spectrum extracted from the PSF core is softer than the true spectrum. However, making use of ChaRT/MARX simulations, we found that the correction for this effect is within the statistical uncertainties in our case.

Figure 7. Spectrum of the pulsar in observation 6684 fitted with the PL model (see Table 3 for the fitting parameters).
larger unaccounted systematic uncertainties (the CTI, gain, and ACIS filter contamination corrections are less accurate for the CC-mode data); therefore, below we will use the more reliable spectral parameters inferred from the ObsID 6684 data.

2.4.2. PWN

We used the ObsID 6684 data to extract the PWN spectra from two regions. The brightest inner component is extracted from the 0.75 < r < 1.25 annulus with the area of 3.14 arcsec$^2$ (see Figure 4). In this case we used the pulsar spectrum as the background spectrum, scaling the normalization according to the simulated PSF shown in Figure 3 (bottom) and taking into account the hardening of the point-source spectrum in the PSF wings (see footnote 11). The fainter outer component is extracted from a polygon region (see Figure 2) with an area of 2600 arcsec$^2$ (excluding the r = 9″ circle around the pulsar). The background was taken from the 40″ × 65″ box shown in Figure 2 (top).

The annulus region of the inner PWN component has 1162 counts (see Table 2 for details), with ≈63% of them coming from the pulsar (treated as a background). The corresponding absorbed flux is $F_{\text{inner}} \approx (1.5 \pm 0.4) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5–8 keV band. The outer PWN region contains 959 counts (54% coming from the source); its absorbed flux is $F_{\text{outer}} \approx (1.7 \pm 0.1) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the same band.

We binned the spectra extracted from the inner and outer regions with a minimum of 50 counts per spectral bin. We then fit the spectra with the absorbed PL model with the hydrogen column density fixed at the best-fit value obtained from the PL fit to the pulsar spectrum, $n_H = 3.45$. For the outer PWN component, we restrict the energy range to 2–8 keV because of the large contribution of the nonuniform background at lower energies (the background contribution decreases from 46% in 0.5–8 keV to 36% in the 2–8 keV band). We find that the PL model provides a good description of the extracted spectra for both the inner and outer PWN. The photon indices are $\Gamma_{\text{outer}} = 1.65 \pm 0.20$ (see Figure 9) and $\Gamma_{\text{inner}} = 1.5–2.1$ (the large uncertainty in $\Gamma_{\text{inner}}$ reflects systematics due to the subtraction of the pulsar background from the energy dependent wings of the PSF). Thus, the PWN spectra are noticeably softer than the pulsar spectrum. The combined unabsorbed luminosity from the two PWN regions is $L_{\text{pwn}} = (3.2–3.7) \times 10^{33} d_6^{2.5}$ erg s$^{-1}$ in the 0.5–8 keV band (see Table 3 for details).

3. DISCUSSION

In our high-resolution Chandra ACIS observation, we discovered the X-ray PWN around the young, energetic pulsar J1617. Below we discuss the pulsar and PWN properties, compare them with those of other young pulsars, and discuss the connection between J1617 and the nearby HESS J1616.

3.1. Pulsar

The X-ray luminosity of J1617 is ≈15% lower than that reported by BA02 from the XMM-Newton observations. The discrepancy is not surprising because the broader PSF of XMM-Newton includes both the pulsar and PWN contributions. Once these components are added together, the Chandra and XMM-Newton flux (and spectral slope) measurements are in agreement within their uncertainties. The 44% pulsed fraction measured from the CC-mode data is somewhat lower than that reported by BA02. The unabsorbed contribution from the inner PWN, resolved in the deconvolved images (see Figures 3 and 4), is ≈10%–15%, resulting in the intrinsic pulsar’s pulsed fraction of ≈50%.

The X-ray efficiency of the J1617 pulsar, $\eta_{\text{psr}} \equiv L_{\text{psr}} / \dot{E}$, is typically among young pulsars (see Figure 10, top). However, the spectrum of J1617 is surprisingly hard, $\Gamma_{\text{psr}} \approx 1.1$. Very few pulsars (J1509–58, J1420–6048, J1846–0258) possibly exhibit similarly hard X-ray spectra (KP08 and references therein), but the accuracies of the spectral slope measurements in those pulsars are lower than in J1617. The fact that the energy spectrum of the pulsar magnetospheric X-ray emission can be so hard has important implications for pulsar emission models. For instance, the models that interpret the nonthermal X-ray emission as synchrotron emission from the particles produced in a pair cascade predict $1.5 < \Gamma < 2$ (e.g., Cheng et al. 1998; Crusius-Wätz et al. 2001), i.e., softer than the spectrum we measured. However, the so-called “full polar cap cascade” models, in which the X-rays are produced by the resonant inverse Compton scattering of the thermal emission from the hot NS surface (Zhang & Harding 2000), can explain harder spectra, with $\Gamma_{\text{psr}} \approx 1$ (Fang & Zhang 2006). Hard spectra ($\Gamma \approx 2/3$) are possible in the models with curvature-radiation-induced cascades in which curvature radiation may dominate synchrotron radiation even below $\sim$10 keV (Harding 2008), although this emission mechanism is more commonly considered for higher energies. Finally, a hard spectrum could be produced via the resonant inverse Compton scattering of the radio photons if this process contributes substantially to the X-ray band (Petrova 2008). Measurements at higher energies with Integral and RXTE suggest a mild softening of the pulsar spectrum, by $\Delta \Gamma \approx 0.2–0.3$ (see Figure 5 in Landi et al. 2007). Such behavior is opposite to the spectral hardening observed in magnetars, which is attributed to comptonization of the thermal emission from the NS surface by the relativistic electrons in the NS magnetosphere (Fernández & Thompson 2007; Baring & Harding 2008).
The lack of a thermal component in the detected pulsar emission might be explained by its intrinsic faintness relative to the strong magnetospheric emission in this young pulsar. However, it is hard to constrain its contribution because, at \( n_{H,22} \approx 3.5 \), the soft thermal X-rays are strongly absorbed by the interstellar medium (ISM).

### 3.2. PWN

Unlike the pulsar, the X-ray efficiency of the J1617 PWN (compact + extended), \( \eta_{pwn} \equiv L_{pwn}/E = 2 \times 10^{-4} d_{5.5}^2 \) in the 0.5–8 keV band, is noticeably lower then those of other young PWNe (Figure 10, middle), except for J1357–6429 (Zavlin 2007). Also, the ratio of the PWN to pulsar luminosities, \( L_{pwn}/L_{psr} \approx 0.18 \) (independent of the poorly known distance), is among the lowest (Figure 10, bottom), and it is significantly lower than the average \( L_{pwn}/L_{psr} \approx 4 \) reported by Kargaltsev et al. (2007a) and KP08. The actual PWN efficiency and the \( L_{pwn}/L_{psr} \) value could be higher for J1617 if the compact PWN component is not completely resolved from the pulsar. An upper limit on the luminosity of the unresolved PWN core follows from the timing analysis (see Sections 2.3 and 3.1). The luminosity of the unresolved core cannot exceed \( \approx 50\% \) of the pulsar luminosity (assuming that the pulsar emission is 100\% pulsed), which still leaves the J1617 PWN underluminous compared to the majority of PWNe (see Figure 10 and the discussion below).

KP08 found that the X-ray efficiencies of PWNe show a very large scatter, \( \eta_{pwn} \sim 10^{-5}–10^{-1} \). The cause of such a large scatter is still not understood. One could attribute the scatter to environmental differences (e.g., ISM pressure and density); however, the surprisingly good correlation between the PWN luminosities and nonthermal pulsar luminosities (with a much smaller scatter, 0.1 \( \lesssim L_{pwn}/L_{psr} \lesssim 10 \); KP08) calls for a different explanation because \( L_{psr} \) does not depend on the environment.

The deconvolved Chandra images of J1617 suggest a compact structure at a distance of \( \sim 1'' (= 9.7 \times 10^{16} d_{5.5} \text{ cm}) \) from the pulsar (see Figure 4), which could be a torus beyond the termination shock in the pulsar wind. Since we expect the pulsar to be within the interior of a young SNR filled with a hot plasma, we assume that the pulsar is moving subsonically and estimate the ambient pressure as

\[
p_{amb} \sim f_\Omega (4\pi c r_s^2)^{-1},
\]

where \( r_s \) is the termination shock radius in the equatorial plane, and the factor \( f_\Omega \) takes into account possible anisotropy of the pulsar wind. For J1617, this estimate gives \( p_{amb} \sim 1.7 \times 10^{-8} f_\Omega (r_s/5 \times 10^{16} \text{ cm})^{-2} \) dyn cm\(^{-2} \) (we scale \( r_s \) to the smaller value because the termination shock radius is expected to be smaller than the radius of the X-ray torus). We should note that, at \( f_\Omega (r_s/5 \times 10^{16} \text{ cm})^{-2} \sim 1 \), the estimated ambient pressure looks uncomfortably high compared to that expected in the interiors of an SNR for “standard” SNR parameters. For instance, in the adiabatic (Sedov–Taylor) stage of the SNR evolution, the central pressure is a factor of 2–3 lower than the pressure just behind the forward SNR shock, \( p_{fs} = (3/4) \rho_0 v_s^2 = (3\rho_0/25)^{3/5} (E_0/\pi)^{2/5} t^{-6/5} = 3.8 \times 10^{-9} n_0^{3/5} E_{51}^{2/5} t_4^{-6/5} \) dyn cm\(^{-2} \), where \( \rho_0 = 1.67 \times 10^{-22} n_0 \text{ g cm}^{-3} \) is the mass density of the unperturbed ISM ahead of the shock, \( E_0 = 10^{51} E_{51} \text{ erg} \) is the energy of the SN explosion, and \( t_4 \) is the SN age in units of 10\(^3\) yr. To obtain the central pressure of \( \sim 2 \times 10^{-8} \) dyn cm\(^{-2} \), we have to assume an SNR age smaller than the spin-down age of the pulsar and/or a sufficiently high ISM density (e.g., \( n_0 \sim 5 \text{ cm}^{-3} \) for \( t = 3 \text{ kyr}, E_{51} = 1 \)). We should note, however, that the actual central pressure could be somewhat higher than that given by the idealized self-similar solution, as hinted by the analysis of the young, well-resolved Vela and B1706–44 PWNe (\( p_{amb} \sim 0.8 \times 10^{-8} \) dyn cm\(^{-2} \); see Table 2 in Kargaltsev et al. 2007a).

As the inferred pressure is already quite high, we believe it is unlikely that the X-ray PWN is more compact than it follows from our image analysis (which would imply that the true PWN luminosity and its ratio to \( L_{psr} \) are higher than

### Table 2

| Region          | \( n_{H,22} \) | \( X_{-4} \) | \( \Gamma \) | \( \chi^2/\nu \) | \( L_{X,33} \) | \( L_{16} \) |
|-----------------|---------------|-------------|-------------|-----------------|---------------|-------------|
| Inner PWN       | 3.14          | 1162 ± 32   | 732 ± 75   | 430 ± 82        | 5.2           | 2.39 ± 0.46 |
| Outer PWN       | 2610          | 959 ± 31    | 445 ± 21   | 514 ± 37        | 13.9          | (3.44 ± 0.25) × 10^{-3} |

Notes. Source (\( N_{tot} \)), total (\( N_{bg} \)), and background (\( N_{bb} \)) counts are extracted from the regions with the area \( A \) (in arcsec\(^2\)) shown in Figures 2 and 4, in the 0.5–8 keV band. For the inner PWN the uncertainty of the background, \( \approx 10\% \), is mostly systematic (due to the uncertainties involved in the PSF simulation). The mean surface brightness \( S \) is in units of counts ks\(^{-1}\) arcsec\(^{-1}\) in the 0.5–8 keV band.
Figure 10. Top: pulsar luminosity vs. spin-down power $\dot{E}$. Middle: PWN luminosity vs. $\dot{E}$. Bottom: pulsar luminosity vs. PWN luminosity. The top and middle panels show the lines of constant X-ray efficiency, while the dashed line in the bottom panel corresponds to $L_{\text{psr}} = L_{\text{pwn}}$. (Based on the data published by KP08.)

estimated above). Therefore, we believe that most of the PWN emission is resolved in the Chandra image shown in Figure 4, and the radiative efficiency of the shocked pulsar wind in the J1617 PWN is well below the average. The low PWN luminosity cannot be attributed to inefficient pair production in the pulsar magnetosphere because the nonthermal pulsar luminosity is close to its typical value. However, the faintness of the PWN could be attributed to inefficient particle acceleration on the way to (or at) the termination shock. The physical mechanism responsible for particle acceleration is currently unknown, and the processes occurring upstream of the shock are poorly understood (Arons 2008a; Kirk et al. 2007). We can only speculate that these processes may depend on the angle between the pulsar magnetic and rotation axes (e.g., a larger misalignment of the axes may lead to faster conversion of the magnetic field energy to the particle energy via more efficient magnetic field reconnection). They may also depend on the termination shock radius, which, in turn, depends on the ambient pressure. For instance, if $r_t$ is small, there may not be enough time for the dissipative processes to convert the magnetic field energy to the particle energy (e.g., Arons 2008b). Yet, even in this case, most of the pulsar’s rotational energy is being lost as wind, but the wind may have a higher magnetization parameter and lower particle energies than in the case of X-ray bright PWNe (see, e.g., Arons (2008a) for a pulsar wind theory review). A higher than typical ambient pressure (hence a small termination shock radius) is plausible because the young pulsar should be within the host SNR interior (which remains undetected because of the strong X-ray absorption). The wind still should emit synchrotron radiation downstream of the termination shock but possibly at lower frequencies as the characteristic synchrotron frequency is proportional at the electron Lorentz factor squared. Unfortunately, observing at lower X-ray energies or in the optical is impossible because of the strong ISM absorption, but sensitive far-IR and radio

3.3. Connection to HESS J1616–508

J1617 is located $\sim 10'$ east of the TeV source HESS J1616–508 (see Figure 5). Despite the large offset, the young, energetic pulsar is still within the TeV source extent, and it has been considered a plausible candidate for powering the TeV emission (Aharonian et al. 2006; Landi et al. 2007), mainly based on energetics arguments ($L_{\text{TeV}} \sim 10^{-2} \dot{E}$). Extended TeV sources have recently been discovered in the vicinity of a few ($\approx 15$) young pulsars, leading to the suggestion that the TeV emission comes from relic PWNe crushed by the asymmetric SNR reverse shock that arrived at the pulsar location a few kyr ago (e.g., de Jager 2006; Kargaltsev et al. 2007b; Kargaltsev & Pavlov 2007). The original model developed by Blondin et al. (2001) suggests that the synchrotron emitting electrons from the pulsar wind can be swept up by the asymmetric reverse shock to one side of the pulsar. The resulting “offset PWNe” will contain aged electrons that still can produce observable radio synchrotron emission as well as high-energy $\gamma$-ray emission via the inverse Compton scattering of background photons by relativistic electrons.

The high-resolution ACIS observations of J1617 do not reveal a preferential extension of the J1617 PWN toward the TeV source (rather there is a hint of extension in the opposite direction; see Section 2.1 and Figure 1), such as observed in some other TeV sources neighboring young pulsars (Kargaltsev & Pavlov 2007; Pavlov et al. 2008). Therefore, we conclude that there is no convincing evidence linking the TeV source to J1617.

The HESS J1616 field has been observed with several X-ray missions. The XMM-Newton and Suzaku images do not reveal any X-ray sources within the TeV bright part of HESS J1616, making it one of the best examples of a “dark accelerator” (Matsumoto et al. 2007). Yet, the examination of the 30 ks ACIS image covering the central part of the HESS J1616 field reveals

16 Kaspi et al. (1998) have analyzed serendipitous ATCA data but found no evidence of a radio PWN at 1.4 GHz.
the possibly extended source X (see Figure 5 and Section 2.2). This source, however, has a very low X-ray flux resulting in a surprisingly small $L_X/L_{TeV} = (1-2) \times 10^{-3}$ (see Table 2 in Kargaltsev et al. (2007b)). Furthermore, the radio and IR images shown in Figure 5 reveal some diffuse emission and pointlike sources within the central part of HESS J1616. The diffuse emission resembles a shell, while one of the bright IR pointlike sources coincides with the center of the TeV source. Therefore, we speculate that HESS J1616 may consist of two (or more) unresolved sources, one of which still might be associated with HESS J1616, while the other(s) could be associated with the extended radio/IR emission (possibly an SNR or a star forming region). Deeper radio and X-ray observations or TeV observations with higher resolution can test this hypothesis.

4. SUMMARY

We have discovered a surprisingly underluminous PWN around the young, energetic pulsar J1617. The PWN consists of compact and extended components of comparable luminosities. The faintness of the PWN could be attributed to the intrinsically low radiative efficiency of the pulsar wind. We have also obtained an accurate measurement of the pulsar’s X-ray spectrum, which fits an absorbed PL with $\Gamma_{\text{abs}} \approx 1.1$, harder than predicted by the models of synchrotron emission from relativistic electrons/positrons produced in the pair cascade.

J1617 has been considered a plausible counterpart to the offset TeV source HESS J1616; however, the X-ray PWN does not show any asymmetry toward HESS J1616. On the other hand, the archival X-ray, IR, and radio data that cover the central region of HESS J1616 reveal some diffuse emission, allowing for alternative interpretations of the TeV emission.

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REFERENCES

Aharonian, F., et al. 2006, ApJ, 636, 777
Aoki, T., Dotani, T., & Mitsuda, K. 1992, IAUC 5588
Arons, J. 2008a, in Springer Lecture Notes on “Neutron Stars and Pulsars, 40 Years after the discovery”, ed. W. Becker (arXiv:0708.1050v1)
Arons, J. 2008b, in AIP Conf. Proc. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnetars, and More, ed. C. Bassa, A. Cumming, V. M. Kaspi, & Z. Wang (Melville, NY: AIP), 200
Baring, M. G., & Harding, A. K. 2008, in AIP Conf. Proc. 968, Astrophys. Compact Objects (Melville, NY: AIP), 93
Baumgartner, W. H., & Mushotzky, R. F. 2006, ApJ, 639, 929
Becker, W., & Aschenbach, B. 2002, in Proc. 270. WE-Heraeus Semin. on Neutron Stars, Pulsars and Supernova Remnants, ed. W. Becker, H. Lesch, & J. Trümper, MPE Report (Garching bei München: Max-Planck-Institut für Extraterrestrische Physik), 64 (BA02)
Benjamin, R. A., et al. 2003, PASP, 115, 953
Blondin, J., Chevalier, R., & Frierson, D. 2001, ApJ, 563, 806
Bock, D., Large, M. I., & Sadler, E. M. 1999, AJ, 117, 1578
Buccheri, B., et al. 1983, A&A, 128, 245
Chang, C., Konopelko, A., & Cui, W. 2008, ApJ, 682, 1177
Cheng, K. S., Gil, J., & Zhang, L. 1998, ApJ, 493, L35
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
Crusius-Wätzl, A. R., Kunzl, T., & Lesch, H. 2001, ApJ, 546, 401
de Jager, O. 2006, in 26th IAU Meeting On the Present and Future of Pulsar Astronomy, Joint Discussion 2, JD02, 53
de Luca, A., Caraveo, P. A., Mereghetti, S., Tiengo, A., & Bignami, G. F. 2007, ApJSS, 308, 231
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Fang, J., & Zhang, L. 2006, ApJ, 653, 573
Fernández, R., & Thompson, C. 2007, ApJ, 660, 615
Gaensler, B. M., & Slane, P. O. 2006, ARA&A, 44, 17
Garmire, G. P., Garmire, A. B., Burrows, D. N., & Pavlov, G. G. 1999, BAAS, 31, 1427
Gotthelf, E. V., Petre, R., & Hwang, U. 1997, ApJ, 487, L175
Kargaltsev, O., & Pavlov, G. G. 2007, ApJ, 670, 655
Kargaltsev, O., & Pavlov, G. G. 2008, in AIP Conf. Proc. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnetars, and More, ed. C. Bassa, A. Cumming, V. M. Kaspi, & Z. Wang (Melville, NY: AIP), 171 (KP08)
Kargaltsev, O., Pavlov, G. G., & Garmire, G. P. 2007a, ApJ, 660, 1413
Kargaltsev, O., Pavlov, G. G., & Garmire, G. P. 2007b, ApJ, 670, 643
Kaspi, V. M., Crawford, F., Manchester, R. N., Lyne, A. G., Camilo, F., D’Amico, N., & Gaensler, B. M. 1998, ApJ, 503, L161
Kaspi, V. M., Roberts, M. S. E., & Harding, A. K. 2006, in Compact Stellar X-ray Sources, ed. W. H. G. Lewin, & M. van der Klis (Cambridge: Cambridge Univ. Press), 279
Kirk, J. G., Lyytikäinen, M. Y., & Petri, J. 2007, in Springer Lecture Notes on “Neutron Stars and Pulsars, 40 Years After the Discovery”, ed. W. Becker (arXiv:astro-ph/0703116v2)
Kuiper, L. 2007, in Mutifrequency Behaviour of High-Energy Cosmic Sources, May 28–June 2, Vulcano, Italy (http://workshop2007.iasf-roma.inaf.it/talks/thursday_morning_kuiper.pdf)
Landi, R., De Rosa, A., Dean, A. J., Bassani, L., Ubertini, P., & Bird, A. J. 2007, MNRAS, 380, 926
Lucy, L. B. 1974, A1, 79, 745
Matsumoto, H., et al. 2007, PASJ, 59, 151
Misanovic, Z., Pavlov, G. G., & Garmire, G. P. 2008, ApJ, 685, 1129
Mori, K., Tsunemi, H., Miyata, E., Baluta, C., Burrows, D. N., Garmire, G. P., & Chartas, G. 2001, in ASP Conf. Proc. 251, New Century of X-Ray Astronomy, ed. H. Inoue & H. Kunieda (San Francisco, CA: ASP), 576
Pavlov, G. G., Sanwal, D., Garmire, G. F., & Zavlin, V. E. 2002, in ASP Conf. Neutron Ser. 271, Stars in Supernova Remnants ed. O. P. Slane & B. M. Gaensler (San Francisco, CA: ASP), 247
Pavlov, G. G., Sanwal, D., & Teter, M. A. 2004, in IAU Symp. 218, Young Neutron Stars and Their Environments, ed. F. Camilo & B. M. Gaensler (San Francisco, CA: Kluwer), 239
Pavlov, G. G., Kargaltsev, O., & Brisken, W. F. 2008, ApJ, 675, 683
Pavlov, G. G., Kargaltsev, O., & Wong, J. 2008, Am. Astron. Soc., HEAD Meeting 10, 12.07
Petrova, S. A. 2008, MNRAS, 383, 1413
Rudak, B., & Dyks, J. 1999, MNRAS, 303, 477
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Torii, K., Gotthelf, E. V., Vasisht, G., Dotani, T., & Kinugasa, K. 2000, ApJ, 534, L71
Torii, K., et al. 1998, ApJ, 494, L207
Tsunemi, H., Mori, K., Miyata, E., Baluta, C., Burrows, D. N., Garmire, G. P., & Chartas, G. 2001, ApJ, 554, 496
Vink, J. 2004, ApJ, 604, 693
Zavlin, V. E. 2007, ApJ, 665, 143
Zhang, B., & Harding, A. K. 2000, ApJ, 532, 1150