X-RAY EMISSION FROM PSR J1809–1917 AND ITS PULSAR WIND NEBULA, POSSIBLY ASSOCIATED WITH THE TeV GAMMA-RAY SOURCE HESS J1809–193

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ABSTRACT

We detected the 50 kyr old pulsar J1809–1917, and resolved its pulsar wind nebula (PWN) with the Chandra X-Ray Observatory. The pulsar spectrum fits a power-law+blackbody (PL+BB) model, with a photon index $\Gamma_{\text{psr}} = 1.2 \pm 0.6$ and $T \approx 2 \text{MK}$ for $n_H \approx 0.7 \times 10^{22} \text{cm}^{-2}$. At a distance of 3.5 kpc, the luminosities of the PL and BB components are $(4 \pm 1) \times 10^{31} \text{ergs s}^{-1}$ (in 0.5–8 keV) and $\sim 1 \times 10^{32} \text{ergs s}^{-1}$ (bolometric), respectively. The bright inner PWN component of a 3″ × 12″ size is elongated in the north-south direction (with the pulsar close to its south end) and immersed in a larger (20″ × 40″), similarly elongated outer PWN component. The PWN shape can be explained by the ram pressure confinement of the pulsar wind due to the supersonic motion of the pulsar. The PWN spectrum fits an absorbed PL model with $n_H \approx 0.7 \times 10^{22} \text{cm}^{-2}$, $\Gamma_{\text{pwn}} = 1.4 \pm 0.1$, and a 0.5–8 keV luminosity of $\approx 4 \times 10^{32} \text{ergs s}^{-1}$. The compact PWN is surrounded by a large-scale (≈4′ × 4′) emission, more extended southward of the pulsar, i.e., in the direction of the alleged pulsar motion. To explain the extended X-ray emission ahead of the moving pulsar, one has to invoke strong intrinsic anisotropy of the pulsar wind, or assume that this emission comes from a relic PWN swept by the reverse SNR shock. The extension of the large-scale X-ray emission toward the center of the unidentified TeV source HESS J1809–193 suggests an association between this source and J1809–1917. An alternative source of relativistic electrons powering HESS J1809–193 might be the serendipitously discovered X-ray source CXOU J180940.7–192544. In addition to the cosmic microwave background radiation or starlight background, the seed photons for Compton up-scattering to TeV energies might be supplied by bright infrared emission from molecular/dust clouds seen within HE SSS J1809–193.

Subject headings: ISM: individual (IRAS 18067–1927, IRAS 18067–1921, HESS J1809–193) — pulsars: individual (PSR J1809–1917) — X-rays: individual (CXOU J180940.7–192544, CXOU 180933.3–192959)

1 Online material: color figure

1. INTRODUCTION

Chandra and XMM-Newton observations have established the ubiquity of X-ray pulsar wind nebulae (PWNe) around young rotation-powered pulsars (see the reviews by Kaspi et al. 2006 and Gaensler & Slane 2006). The X-ray PWN emission is produced by relativistic particles gyrating in the magnetic field downstream of the termination shock in the pulsar wind (Kennel & Coroniti 1984; Arons 2004). Most of the PWNe have been discovered around young ($\tau \approx 50$ kyr) pulsars. The innermost parts of the young PWNe often show axisymmetric morphologies, including toroidal structures and jets along the pulsar’s spin axis. Recently, it has become apparent that PWNe accompanying older pulsars can also be quite luminous (e.g., McGowan et al. 2006). Many of these older PWNe exhibit cometary morphologies indicating that the pulsar wind is confined by the ram pressure caused by the supersonic motion of the pulsar in the ambient medium. Studying X-ray PWNe of various ages helps us to understand the nature and evolution of the ultrarelativistic pulsar winds and their interaction with the ambient medium.

An interesting object for such investigations is PSR J1809–1917 (hereafter J1809). The discovery of this radio pulsar ($P = 82.7 \text{ ms}$) in the Parkes Multibeam Pulsar Survey 1 was reported by Morris et al. (2002). The pulsar’s dispersion measure, $DM = 197 \text{ cm}^{-3} \text{ pc}$, and the Galactic electron distribution models by Taylor & Cordes (1993) and Cordes & Lazio (2002) give distances to the pulsar of 3.7 and 3.5 kpc, respectively. J1809, with a spin-down age $\tau \approx P/2\dot{P} = 51 \text{ kyr}$ and a spin-down power $\dot{E} \approx 4 \pi^2 \dot{P} \dot{P}^{-3} \approx 1.8 \times 10^{36} \text{ ergs s}^{-1}$, is somewhat older and less energetic than the famous Vela pulsar ($\tau \approx 11 \text{ kyr}$, $\dot{E} = 6.9 \times 10^{36} \text{ ergs s}^{-1}$), which is accompanied by a remarkable PWN resolved in radio (Dodson et al. 2003b) and X-rays (Pavlov et al. 2003, and references therein). However, it is much more energetic than typical “middle-aged” pulsars such as B0656+14 ($\tau \approx 110 \text{ kyr}$, $\dot{E} = 3.8 \times 10^{34} \text{ ergs s}^{-1}$) and Geminga ($\tau \approx 340 \text{ kyr}$, $\dot{E} = 3.2 \times 10^{34} \text{ ergs s}^{-1}$), whose PWNe are very faint (e.g., Pavlov et al. 2006).

J1809 is young enough to look for a remnant of the supernova that created the pulsar. Deep radio observations by Brogan et al. (2004) have revealed two compact H II regions and two SNRs, G11.03−0.05 and G11.18+0.11, projected near the pulsar (the pulsar’s Galactic coordinates are $l = 11.094^\circ, b = +0.080^\circ$). The distances to the SNRs, estimated from the radio surface brightness—diameter ($\Sigma-D$) relation (Case & Bhattacharya 1998), are $\sim 16$ and $\sim 17$ kpc, respectively. However, given the very large uncertainty of the $\Sigma-D$ relation for faint SNRs, the association of J1809 with one of the SNRs cannot be ruled out, despite the discrepant distance estimates. Brogan et al. (2004) estimated that the pulsar would need to have a transverse speed of about 200 or 140 km s$^{-1}$ to originate from the geometrical center of G11.03−0.05 or G11.18+0.11, respectively, assuming that all three are at the same distance of 4 kpc, and that the pulsar’s true age is $50 \text{ kyr}$. The estimated speeds are close to the average speeds recently measured for a large sample of radio pulsars by Hobbs et al. (2005).

Before the detailed radio studies were carried out, the region had been observed by ASCA, first as part of the Galactic plane

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1. See http://www.atnf.csiro.au/research/pulsar/pmsurv/.
The straight line shows the approximate symmetry axis of the X-ray PWN. The observed large-scale emission was attributed to the pulsar position. No pulsar was detected in these X-ray observations. The observed large-scale emission was attributed to a new SNR, dubbed G11.0+0.0. Bamba et al. (2003) found that the X-ray spectrum of the putative SNR fits the absorbed power-law (PL) model with photon index $\Gamma = 1.6 \pm 0.3$, hydrogen column density $n_{\text{H}} = n_{\text{HI}}/10^{22} \text{ cm}^{-2} = 0.8 \pm 0.3$, and $0.7-10$ keV flux of $3.8 \times 10^{-12} \text{ ergs cm}^{-2} \text{s}^{-1}$. Using the best-fit $n_{\text{HI}}$, and assuming that the mean density in the Galactic plane is $1 \text{ H cm}^{-3}$, Bamba et al. (2003) estimated a distance of 2.6 kpc, which gives an X-ray luminosity of $\approx 3.7 \times 10^{33} \text{ ergs s}^{-1}$ (in $0.7-10$ keV). These authors suggested that G11.0+0.0 could be a Crab-like (plerionic) SNR.

Study of the J1809 field has become particularly interesting after the recent discovery of the TeV $\gamma$-ray source HESS J1809–193 (hereafter HESS J1809; Aharonian et al. 2007). The brightest part of this source is firmly detected for up to $12''$–$15''$ from the peak of the TeV surface brightness located at R.A. $= 18^h09^m48^s$, decl. $= -19^\circ25'00''$. Given the small angular separation ($\approx 8'$) between J1809 and the center of the HESS source, and the TeV luminosity $L_{\gamma} \approx 2 \times 10^{44} \text{ ergs s}^{-1} \approx 0.12 E_{65} P_{8.5}$, it seems plausible that the HESS source could be powered by this pulsar.

In this paper, we describe the results of a Chandra observation of PSR J1809–1917 and its compact synchrotron nebula, and discuss its possible connection to HESS J1809. We also describe the multiwavelength properties of objects located within the central part of HESS J1809, including two newly discovered X-ray sources, and discuss their relation to HESS J1809. The details of the observation and the data analysis are presented in § 2. In § 3, we discuss possible interpretations of the PWN morphology, describe inferences from the pulsar spectrum, and speculate on the nature of HESS J1809 and its relation to the other sources in the field. Our main results are summarized in § 4.

2. OBSERVATIONS AND DATA ANALYSIS

J1809 was observed with the Advanced CCD Imaging Spectrometer (ACIS) on board Chandra on 2004 July 21 (ObsID 3853). The useful scientific exposure time was 19,955 s. The observation was carried out in Faint mode, and the pulsar was imaged on the S3 chip, $\approx 0.72''$ off-axis. The other ACIS chips activated during this observation were S1, S2, S4, I2, and I3. The detector was operated in Full Frame mode, which provides a time resolution of 3.24 s. The data were reduced using the Chandra Interactive Analysis of Observations (CIAO) software (ver. 3.2.1; CALDB, ver. 3.0.3).

2.1. Images

Figure 1 shows the ACIS-S3 image of the region around J1809. An extended X-ray source is clearly seen in the image around R.A. $= 18^h09^m43.123^s$, decl. $= -19^\circ17'38.17''$ (these are the coordinates of the center of the brightest pixel). The difference of $0.5''$ between this position and the radio position from Morris et al. (2002) is within the uncertainty of absolute Chandra astrometry.
significant large-scale extended emission, concentrated at the lower half of the S3 chip (south of the pulsar). The morphology of this emission (see also the ASCA image in Fig. 4c) indicates that it possibly extends farther south, but may not be discernible on the S2 chip because of its lower sensitivity.

The only source on the S2 chip detected above the 3 $\sigma$ level is located at R.A. = 18$^h$09$^m$40.725$^s$, decl. = $-$19$^\circ$25$'$44.10$''$ (the 1 $\sigma$ centroid uncertainty is 0.28$''$ and 0.29$''$ in right ascension and declination, respectively), well within the brightest central part of HESS J1809 (about 2$'$ west of its nominal center position; see Fig. 4). We designate this source CXOU J180940.7–192544 (hereafter Ch1). Although Ch1 appears to be extended in the ACIS image, the point spread function (PSF) simulation shows that this is likely the result of the off-axis location (off-axis angle $\theta = 7.4'$). We find no significant large-scale nonuniformities in the X-ray background on the S2 chip (see Fig. 4).

We have also examined the S1 chip image, and found only one source detected above the 3 $\sigma$ level. The source, CXOU 180933.3–192959 (hereafter Ch2), is located at R.A. = 18$^h$09$^m$33.336$^s$, decl. = $-$19$^\circ$29$'$59.89$''$ (the 1 $\sigma$ centroid uncertainty is 0.70$''$ in right ascension and 0.74$''$ in declination), which is about 6$'$ from the center of HESS J1809. The X-ray source is consistent with being pointlike; however, due to the broadened PSF (FWHM $\approx 10''$) at the large off-axis angle (11.8$'$), a compact extended source cannot be ruled out. We have also searched for diffuse emission features on the S1 chip, and produced an image corrected for the exposure map nonuniformities (see Fig. 4b). In this image, the X-ray emission is systematically brighter toward the western edge of the S1 chip, probably due to the imperfection of the monoenergetic (2 keV) exposure map correction at large off-axis angles (see, however, § 2.5). We found no traces of the radio SNRs G11.03–0.05 and G11.18+0.11 in the ACIS images (see Fig. 4).

2.2. Spectral Analysis

2.2.1. PWN Spectrum

We extracted the PWN spectra from two elliptical regions shown in Figure 1 (top right). The smaller elliptical region (of 25.1 arcsec$^2$ area) encompasses the brighter inner PWN, while the larger elliptical region (of 399.4 arcsec$^2$ area) includes the outer PWN component of a lower surface brightness. To avoid the contamination of the PWN spectrum by the pulsar, we excluded from these regions the circular region of 1.46$''$ radius centered on the brightest pixel. The background (367 counts in 5202 arcsec$^2$ area; 0.3–8 keV band) was measured from the 37$''$ $< r < 55''$ annulus centered on the pulsar. The total number of counts extracted from the smaller and larger elliptical regions (excluding the 1.46$''$ radius circle) are 153 and 365, of which 99.2% and 92.4% are expected to come from the source, which gives 151 $\pm$ 12 and 337 $\pm$ 19 PWN counts in the two regions. The observed PWN fluxes (in the 1–6 keV band) are $F_{\text{inner}} = (8.1 \pm 0.7) \times 10^{-14}$ and $F_{\text{pwn}} = (14.7 \pm 0.8) \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ for the inner and the entire (inner+outer) PWN, respectively. The corresponding average intensities are $I_{\text{inner}} = (4.4 \pm 0.4) \times 10^{-15}$ and $I_{\text{pwn}} = (3.7 \pm 0.2) \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$.

To investigate the PWN spectral properties, we first fit the spectra for each of the two PWN regions with the absorbed PL model, allowing the hydrogen column density, $n_{\text{H}}$, to vary. These fits result in spectral slopes $\Gamma_{\text{pwn}} \approx 1.2$–2.0 and $n_{\text{H},22} \sim 0.5$–1.1 (the ranges correspond to the 68% confidence level for a single interesting parameter). The difference in the best-fit parameters for the inner and the entire PWN (see Fig. 5) is statistically insignificant. In particular, we see no spectral softening (expected due to synchrotron cooling) in the spectrum extracted from the...
larger region (the entire PWN) compared to the spectrum of the inner PWN. Therefore, we will use the better constrained best-fit parameters for the entire PWN below (see Figs. 6 and 7), whenever we refer to the PWN spectral properties.

Given J1809’s dispersion measure, DM = 197 cm\(^{-3}\) pc (i.e., electron column density \(n_e = 6.08 \times 10^{20} \text{ cm}^{-2}\)), the \(n_{11.22}\) value of 0.72 (obtained from the fit to the spectrum of the entire PWN) corresponds to the ISM ionization degree \(n_e/n_{\text{H}} \approx 8.4\%\), only slightly below the commonly used value of 10%, which corresponds to \(n_{11.22} = 0.61\). The total Galactic H\(\text{I}\) column density in this direction is \(1.8 \times 10^{22} \text{ cm}^{-2}\) (Dickey & Lockman 1990).

The isotropic luminosity of the entire (inner+outer) X-ray PWN is

\[
L_{\text{pwn}} = 4\pi d^2 F_{\text{pwn}} \approx (3.9 \pm 0.3) \times 10^{32} d_{3.5}^{-2} \text{ ergs s}^{-1}
\]

in the 0.5–8 keV band (\(d_{3.5} = d/3.5 \text{ kpc}\)), with approximately equal contributions from the outer and the inner PWN components (see Table 1).

We have also attempted to fit the spectrum of the faint large-scale emission (within the ellipse in Fig. 4a, excluding the compact PWN and the point sources; 13.2 arcmin\(^2\) area) surrounding J1809 and its compact PWN. Because of the low surface brightness of this emission and large background contribution (\(\sim 65\%\)), the spectral fits yield inconclusive results. With the absorption fixed at \(n_{11.22} = 0.72\), the fits with single PL and thermal plasma\(^4\) models give \(\Gamma = 2.3 \pm 0.3\) (\(\chi^2 \approx 2\)) and \(kT = 0.67 \pm 0.08\) keV (\(\chi^2 \approx 3\)). The main contribution to the large values of \(\chi^2\) comes from high-energy channels (\(\geq 4\) keV and \(\geq 2\) keV for PL and MEKAL, respectively), which suggests either a mixture of thermal and hard nonthermal emission, or varying \(\Gamma\) or \(kT\) within the extraction region. The measured flux, independent of the model, is \(F_{\text{ext}} \sim 5 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}\) in the 0.8–7 keV band, which corresponds to an average surface brightness \(I_{\text{ext}} \sim 1 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}\). The unabsorbed flux, obtained from the PL model, is \(F_{\text{ext}} \sim 8 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}\) in the 0.5–8 keV band.

2.2.2. Pulsar Spectrum

To minimize the contamination by the PWN, the pulsar spectrum was extracted from a small circular aperture (green circle in the bottom panel of Fig. 2) with a radius of 1.5 ACIS pixels (\(\approx 0.74''\), 85% encircled energy radius), while the background was taken from the 10 arcsec\(^2\) region between the white circle and white ellipse in the bottom panel of Figure 2. The background region includes the bright part of the PWN; it contributes \(\approx 8\) counts to the total of \(67\) counts extracted from the source aperture. Given the small number of counts and the large background contribution, we chose not to subtract the background, but rather to fit it simultaneously with the source spectrum, using an additional absorbed PL model with the same \(n_{\text{H}}\) as that of the source. The pulsar’s absorbed flux is \(F_{\text{psr}} = (1.8 \pm 0.2) \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}\) in the 1–6 keV band (aperture corrected).

\(^3\) We have also measured the spectrum of the outer PWN separately, and found that the best-fit PL parameters are consistent with those obtained for the inner PWN and the entire PWN spectra, but that their uncertainties are larger because of the larger background contribution.

\(^4\) The model “MEKAL” in XSPEC, with standard abundance.
Although the absorbed PL model formally fits the pulsar spectrum, indicating a soft PL ($\Gamma_{\text{psr}} \approx 2.6$; see Table 2 and Figs. 8 and 9), the fit yields $n_{11,22} \approx 0.4$, which is smaller than that for the PL fit to the entire PWN spectrum. To obtain a better constrained fit, we fixed the hydrogen column density at $n_{11,22} = 0.72$, obtained above from the PL fit to the PWN spectrum. With this $n_{11,22}$, the single PL fit is still acceptable, but it yields a large photon index, $\Gamma = 3.2 \pm 0.4$, suggesting a thermal emission contribution. A two-component, PL+BB fit yields reasonable values for the fitting parameters (see Table 2 and Figs. 8–10), which, however, are poorly constrained because of the small number of photons detected. The slope of the PL component is $\Gamma_{\text{psr}} = 1.2 \pm 0.6$, and its unabsorbed luminosity is $L_{\text{psr}} \sim 4 \times 10^{31}d_{2.5}^{-2}\text{ergs s}^{-1}$ in the $0.5$–$8$ keV band. The temperature and the projected area of the BB component are strongly correlated (see Fig. 10), which results in large uncertainties for these parameters. The best-fit temperature for the BB component is $T \approx 2$ MK, while the projected emitting area, $A \sim 3 \times 10^9d_{2.5}^2\text{m}^2$, is smaller than that of the surface of a neutron star ($\pi R^2 \sim 3 \times 10^8\text{m}^2$), but larger than the conventional polar cap area $A_{\text{pc}} = 2\pi^2 R^2 \sin \theta \approx 2.5 \times 10^5\text{m}^2$. The corresponding bolometric luminosity, $L_{\text{bol}} \equiv 4\sigma T^4 \approx 1 \times 10^{32}d_{2.5}^{-2}\text{ergs s}^{-1}$.

2.2.3. Ch1 Spectrum

We extracted 99 events from the elliptical region (with semimajor and semiminor axes of $10.3''$ and $6.3''$, respectively) centered on the best-fit position of Ch1, and conforming to the shape of the off-axis PSF. Based on the PSF simulation, the extraction region contains $95\%$ of point-source counts. The expected background contribution, 44 counts, is negligible ($\approx 4\%$ of the total number of counts). The measured source flux in $0.8$–$7$ keV is $F_{\text{Ch1}} = (8.6 \pm 0.9) \times 10^{-12}\text{ergs cm}^{-2}\text{ s}^{-1}$, after correcting for vignetting and finite extraction aperture size. The spectrum is fit well by an absorbed PL model (see Table 3) with $n_{11,22} = 1.2 \pm 0.4$ and $\Gamma = 1.4 \pm 0.4$. The unabsorbed flux in $0.5$–$8$ keV is $F_{\text{Ch1, unabs}} \approx 1.4 \times 10^{-13}\text{ergs cm}^{-2}\text{ s}^{-1}$. 
2.2.4. Ch2 Spectrum

We extracted 90 events within a 30'' radius around the best-fit position of Ch2. Based on the PSF simulation, the extraction region contains ≈85% of the source counts if Ch2 is a point source. The background contributes ≈32 counts, (i.e., ≈36% of the total number of counts). The measured 0.8–7 keV source flux is \( F_{\text{Ch2}} \approx 9 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1} \), after correcting for vignetting and finite extraction aperture size (assuming a point source). The thermal plasma (MEKAL) model fits the Ch2 spectrum best, although fits with absorbed PL and BB models are also acceptable (see Table 3 for details).

2.3. Timing

The 3.24 s time resolution of this observation is insufficient to observe the 82.7 ms pulsations from the pulsar. We found no significant variability in the Ch1 and Ch2 light curves.

2.4. Archival X-Ray Data

The region of interest has been previously observed by ASCA for 39 ks (Bamba et al. 2003). The ASCA GIS image in Figure 4c shows a region of enhanced X-ray brightness that encompasses J1809 and its compact PWN; however, the diffuse X-ray emission also extends at least \( \approx 10' \) southward, covering the region of the HESS J1809 that is brightest in TeV.

The field was also partly observed by the XMM-Newton as a part of the Galactic plane survey (PI: R. Warwick). A pointlike object is clearly seen at the pulsar position in the combined EPIC (MOS1+MOS2+PN) image shown in Figure 4. However, the short 8 ks exposure, the off-axis location, and the high EPIC background do not allow the detection of the faint extended component, while the compact PWN cannot be resolved from the pulsar because of the broad PSF of XMM-Newton.

2.5. Optical-IR-Radio Data

To understand the nature of the X-ray sources Ch1 and Ch2, projected within the HESS source image, and to look for other sources that could be related to the TeV emission, we have examined the field at other wavelengths. We found no counterparts to Ch1 in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) or the Digital Sky Survey (DSS2) catalogs, up to the limiting magnitudes \( K_s = 15.4, H = 16, J = 17.5, R = 19, \) and \( B = 21 \). The nearest optical/NIR source is a 2MASS point source \( (J = 15.45 \pm 0.05, H = 13.10 \pm 0.05, K = 12.06 \pm 0.04) \) located at R.A. = 18\(^{h}\)09\(^{m}\)40.92\(^{s}\), decl. = \(-19^\circ 25' 45.7''\). The 3.2'' offset from the best-fit Ch1 position substantially exceeds the position uncertainty of \( \approx 0.4'' \). Figure 4 shows that Ch1 is projected very close to the extended source A seen in the radio and IR images.

5 See http://archive.eso.org/dss/dss.

| Model          | \( n_{\text{H}22} \) | \( \chi^2 \) | \( \Gamma \) | \( \chi^2 \text{/dof} \) | \( L_X \) |
|----------------|----------------|-------------|-------------|----------------|---------|
| Entire PWN.....| 0.72           | 35.61        | 1.41        | 0.82/34        | 3.89/0.24 |
| Inner PWN..... | 0.98           | 30.63        | 1.85        | 335/526        | 2.21/0.19 |

**Notes.**—The fits are for fixed \( n_{\text{H},22} = n_{\text{H}}/10^{22} \text{ cm}^{-2} \). The uncertainties are given at the 68% confidence level for a single interesting parameter.

- Spectral flux in units of \( 10^{-6} \) photons cm\(^{-2} \) s\(^{-1} \) keV\(^{-1} \) at 1 keV.
- We use the C-statistic (Cash 1979) for the inner PWN (which has fewer counts) and the \( \chi^2 \) statistic for the entire PWN.
- Unabsorbed isotropic luminosity in the 0.5–8 keV band, in units of \( 10^{32} \) ergs s\(^{-1} \).

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**TABLE 1**

PL Fits to the PWN Spectrum

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**FIG. 6.** Entire (outer + inner) PWN spectrum, fitted with the PL model (see Table 1 for details).

**FIG. 7.**—Confidence contours (68% and 90%) for the PL fit to the entire PWN spectrum (for a fixed \( n_{\text{H},22} = 0.72 \)). The PL normalization is in units of \( 10^{-6} \) photons cm\(^{-2} \) s\(^{-1} \) keV\(^{-1} \) at 1 keV. The dashed lines are the loci of constant unabsorbed flux in the 0.5–8 keV band; the flux values near the curves are in units of \( 10^{-13} \) ergs cm\(^{-2} \) s\(^{-1} \).
The only NIR/optical source within the 5″ radius of the Ch2 position is a star, NOMAD1 0705−0568334 in the NOMAD catalog (Zacharias et al. 2005), offset by only 0.9″ from Ch2. Given the relatively large uncertainty of the Ch2 position (see § 2.1), the positions of the star and Ch2 can be considered coincident. The X-ray-to-optical flux ratio, $F_X/F_O \sim 2 \times 10^{-3}$, is typical for a K star with coronal X-ray emission (Maccacaro et al. 1988). The soft X-ray spectrum of Ch2 and the optical−NIR magnitudes of the star ($B = 14.96, V = 14.66, R = 14.19, J = 13.35, H = 12.84, and K = 12.72$) support such an interpretation. No Ch2 counterpart is seen in the NVSS 20 cm image or in the Spitzer 8 and 24 μm images.

The Multi-Array Galactic Plane Imaging Survey (MAGPIS) 20 cm image (5.4″ synthesized beam size) and the 25″ resolution images by Brogan et al. (2004) show two bright compact radio sources (marked A and B in Fig. 4) projected near the HESS source center, with 1.4 GHz spectral fluxes of 0.3 and 0.15 Jy for source A and source B, respectively. Within these sources, 6.7 GHz methanol masers have been detected (Pestalozzi et al. 2005): G10.95+0.02 in source A (peak flux 15 Jy at 6.7 GHz; $V_{LSR} = 24 \pm 1$ km s$^{-1}$; near-distance 3.2 kpc) and G11.03+0.06 in source B (peak flux 0.7 Jy at 6.7 GHz; $V_{LSR} = 20 \pm 1$ km s$^{-1}$; near-distance 2.9 kpc).

Both A and B are also very bright far-IR sources, IRAS 18067−1927 and IRAS 18067−1921 in the IRAS Point Source Catalog, version 2.1 (IPAC Infrared Science Archive), with peak fluxes of 1292 and 513 Jy, respectively, at 60 μm. The Spitzer IRAC 8 μm and MIPS 24 μm images (Figs. 4g, 4h, taken from the GLIMPSE survey) show extended sources of irregular shape at these positions, with characteristic sizes of ~1″. They are not seen in the DSS and 2MASS images, which suggests that they are intrinsically very cold ($T \sim 70$ K) and/or strongly absorbed molecular/dust complexes.

Source A has complex morphology both in the IR and radio (see Fig. 4), and is projected in the vicinity of the HESS source center, but a close-up view in Figure 4f (bottom inset) shows that Ch1 lies just outside the resolved radio emission associated with source A. Therefore, we cannot claim an association between Ch1 and source A at this time.

The Spitzer and MAGPIS images also reveal an extended source with an interesting morphology (shell-like in the 24 μm image), located ~10′ southwest of the HESS J1809 center (see Fig. 4).

The source appears to have an extended nonthermal radio counterpart (G10.87+0.08), clearly seen in the 20 cm image in the same figure, which suggests that the source may be an SNR (Helfand et al. 2006). It is possible that this extended source contributes to the nonuniform X-ray background on the S1 chip (see § 2.1 and Fig. 4). The SNR candidates G11.03+0.05, G11.18+0.11 (Brogan et al. 2004; see Figs. 4b, 4f) are also clearly seen in the MAGPIS 20 cm image.

3. DISCUSSION

The subarcsecond angular resolution of Chandra has allowed us to resolve the compact J1809 PWN, disentangle the pulsar and the extended emission components, and measure their properties.
separately. Thanks to the very low ACIS background, we were also able to detect the faint large-scale emission surrounding the compact PWN. The observation has also provided serendipitous coverage of the central part of the extended TeV source HESS J1809, and revealed two X-ray sources bright enough to permit spectral measurements and accurate determination of their positions. In this section, we discuss some implications of our findings.

3.1. The J1809 PWN

3.1.1. Luminosity and Spectrum

At a plausible distance of 3.5 kpc, the unabsorbed X-ray luminosity of the compact PWN, \( L_{\text{pwn}} \sim 4 \times 10^{32} \text{ ergs s}^{-1} \), corresponds to the X-ray efficiency, \( \eta_{\text{pwn}} \equiv L_{\text{pwn}}/E \sim 2.2 \times 10^{-4} \), similar to those of PWNe around younger and more powerful Vela-like pulsars (see Fig. 11). Some of the detected X-ray PWNe associated with older and less powerful pulsars have similar or higher X-ray efficiencies (e.g., \( \eta_{\text{pwn}} \sim 2 \times 10^{-3} \) and \( 4 \times 10^{-4} \) for J1509–5850 \( [\tau = 150 \text{ kyr}] \) and B0355+54 \( [\tau = 560 \text{ kyr}] \), respectively; O. Kargaltsev et al., in preparation), while others show much lower efficiencies (e.g., \( \eta_{\text{pwn}} \sim 5 \times 10^{-5} \) and \( 7 \times 10^{-6} \) for PRS J1740+1000 \( [\tau = 100 \text{ kyr}] \) and Geminga \( [\tau = 340 \text{ kyr}] \), respectively; O. Kargaltsev et al., in preparation; Pavlov et al. 2006). This indicates that \( \eta_{\text{pwn}} \) is not significantly correlated with \( \tau \) or \( E \), at least for young and middle-aged pulsars \( (\tau \lesssim 1 \text{ Myr}) \), perhaps because, in addition to \( E \) and \( \tau \), it depends on other factors (e.g., the pulsar’s speed and the angle between the spin and magnetic axes).

The spectral slope of the J1809 PWN, \( \Gamma_{\text{pwn}} = 1.4 \pm 0.1 \), is similar to those of the PWNe around Vela-like pulsars (listed in Table 2 of Kargaltsev et al. 2007a, hereafter KPG07a), except for two bow shock PWNe with prominent tails, J1747–2958 (“the Mouse”; Gaensler et al. 2004) and B1757–24 (“the Duck”; Kaspi et al. 2001), which show softer spectra (\( \Gamma = 2.0 \pm 0.2 \) and \( 2.5 \pm 0.3 \), respectively). Comparing the J1809 spectrum with those of older PWNe, we see that it is similar to the spectra of relatively compact PWNe (e.g., \( \Gamma = 1.4 \pm 0.3 \) for the bright part of the B0355+54 PWN; McGowan et al. 2006), but it is harder than the spectra of the extended tails in J1740+1000 and J1509–5850 PWNe (\( \Gamma = 1.8 \pm 0.4 \) and 2.2 ± 0.3, respectively; O. Kargaltsev et al., in preparation). It hints that PWN spectra are correlated with PWN morphology, rather than with the pulsar age and spin-down power.

3.1.2. PWN Morphology

The unknown proper motion of J1809 and the faintness of the surrounding large-scale emission complicate the interpretation of the observed PWN, but its “cometary” appearance strongly suggests that the pulsar’s motion plays a major role.

3.1.2.1. Bow Shock in a Nearly Isotropic Pulsar Wind?

The compact J1809 PWN is elongated approximately along the north-south direction, with the pulsar located much closer to its southern end (see Fig. 1). Such a cometary morphology can be attributed to a bow shock created by the pulsar moving supersonically in the southern direction (\( P.A. \approx 194^\circ \)). The apex of the termination shock (TS) of the pulsar wind is located at the distance

\[
R_b \approx \left( \frac{\dot{E}f_1}{4\pi c (p_{\text{amb}} + p_{\text{ram}})} \right)^{1/2}
\]

ahead of the pulsar. At this distance, the pulsar wind pressure, \( p_w = \dot{E}f_1(4\pi c r_s^2)^{-1} \) (\( f_1 \) takes into account the anisotropy of the pulsar wind), is balanced by the sum of the ambient pressure

\[
p_{\text{amb}} = p_kT(\mu m_H)^{-1} = 1.38 \times 10^{-12} n\mu^{-1} T_4 \text{ ergs cm}^{-3},
\]

and the ram pressure

\[
p_{\text{ram}} = \rho v_r^2 = 1.67 \times 10^{-10} n\mu^2 \text{ ergs cm}^{-3},
\]

where \( T_4 = T/10^4 \text{ K}, v_r = v/10^7 \text{ cm s}^{-1}, \mu \) is the molecular weight, and \( n = \rho/m_H \) is in units of \( \text{cm}^{-3} \). Assuming \( p_{\text{ram}} \gg p_{\text{amb}} \) [or \( \mathcal{M} \gg 1 \), where \( \mathcal{M} = v/c_s \) is the Mach number, and \( c_s = (5kT/3\mu m_H)^{1/2} = 12\mu^{-1/2} T_4^{1/2} \text{ km s}^{-1} \) is the sound speed in the ambient medium], we obtain

\[
R_b = 1.7 \times 10^{17} n^{-1/2} f_1^{1/2} v_r^{-1} \text{ cm}.
\]
The shocked pulsar wind, observed in X-rays as a bow shock PWN, is confined between the TS and the contact discontinuity (CD) surface. For $\mathcal{M} \gg 1$ and a nearly isotropic preshock wind with a low magnetization parameter $\sigma$, the TS acquires a bulletlike shape (Bucciantini et al. 2005, hereafter B05). The distance $R_b$ between the pulsar and the bullet head is given by equation (1), while the CD surface head is at a distance $\approx 1.3 R_b$ from the pulsar. Assuming that the sharp rise in the brightness profile (Fig. 2) at about $3''$ from the pulsar (i.e., $1.6 \times 10^{12} d_{3.5}^3$ cm in the plane of the sky) corresponds to the CD head, we can estimate the pulsar velocity,

$$ v \approx 140 n^{-1/2} d_{3.5}^{-1} \sin i \text{ km s}^{-1} , \tag{2} $$

and the Mach number, $\mathcal{M} \approx 12 n^{-1/2} T_{15}^{1/2} / (1/2) a_{15}^{1/2} d_{3.5}^{-1} \sin i$, where $i$ is the angle between the velocity vector and the line of sight.

The observed projected length, $\sim 12''$, and width, $\sim 3''$, of the inner PWN are close to the length $\sim R_b \sim 15''$, and width, $\sim R_b \sim 2''$, of the TS bullet, as predicted by the B05 models for $\sigma \sim 10^{-3}$. The width of the outer PWN, $\sim 20''$, can be interpreted as the diameter of the CD shell (approximately cylindrical behind the pulsar, with a diameter $\sim 8 R_b \sim 18''$, according to B05).

The B05 models also predict a tail behind the back surface of the TS bullet, where the collimated shocked pulsar wind flows with subrelativistic velocities: 0.1–0.3 c in the inner channel with a cylindrical radius $\sim R_b (\sim 2''$ in our case), and up to 0.8–0.9 c in the outer channel, confined between the cylindrical surfaces with radii $\sim R_b$ and $\sim 4 R_b$. The lack of an extended tail in the ACIS images is puzzling; it could be due to a relatively low Mach number of the pulsar and insufficient sensitivity of the short ACIS exposure.

On the other hand, the shape of the faint thin feature northeast of the inner PWN hints that it may be a bent extension of the inner PWN, which is difficult to explain if this is a strongly collimated, mildly relativistic flow just behind the back surface of the TS bullet (unless the flow is subject to kink instabilities). However, the statistical significance of this feature is too low to draw any definitive conclusions.

### 3.1.2.2. Effects of Pulsar Wind Anisotropy

We should note that the B05 models assume an isotropic pulsar wind ($f_0 = 1$). We know from observations of young pulsars, such as Crab and Vela, that the wind is not isotropic, but is mostly confined to the equatorial plane. In addition, in young PWNe, we often see jets along the pulsar’s spin axis. These jets can be formed by polar outflows originating in the pulsar magnetosphere, or they can be created by tangential inflows just outside the equatorial TS surface converging toward the spin axis (Komissarov & Lyubarsky 2004). We are unaware of MHD PWN models that include both the pulsar wind anisotropy and the ram pressure effects. We can, however, expect that, in the case of an anisotropic wind, the PWN morphology, at least close to the pulsar, would depend on the orientation of the spin axis with respect to the pulsar’s velocity.

As Chandra observations have shown, the spin axis is oriented along the direction of pulsar’s motion in a number of young pulsars (e.g., Ng & Romani 2004). In this case, we expect that the equatorial outflow would form a shell between the TS and the CD surface behind the pulsar, filled by a relativistic plasma with a subrelativistic bulk flow velocity. The morphology of the X-ray emission from such a PWN would be generally similar to that in the case of isotropic wind, although we may expect to see a shell-like (rather than filled) PWN appearance at sufficiently high resolution. Such a structure (“outer tails”) is possibly present in the Geminga PWN (Caraveo et al. 2003; Pavlov et al. 2006). As for the jets coaligned with the pulsar velocity vector, the rear jet is...
expected to be seen along the shell filled by the shocked equatorial wind behind the pulsar (at least, if the jet originates from the pulsar magnetosphere), as observed in the Geminga PWN (Pavlov et al. 2006). The front jet is expected to pierce the head of the shell (as \( f_1 > 1 \) in the jet), and to be seen ahead of the pulsar, unless it is crushed by the ram pressure. The jets could be of quite different brightness and length because of Doppler boosting and different effective pressures in front of and behind the pulsar.

In the case of J1809, the high-resolution images shown in Figure 1 indicate the presence of a narrow structure (with a linear extent of \( \sim 3' \)) just south of the pulsar, which might be interpreted as a front jet. Furthermore, the heavily binned low-resolution image (Fig. 3, bottom right) shows a faint structure extending in the direction of the presumed pulsar’s proper motion. Although tentative, the structure is consistent with the X-ray morphology seen in the ASCA GIS image (Fig. 4c). Therefore, one could speculate that these structures are connected to each other, and could be parts of the front jet. In this interpretation, the rear jet may contribute to the inner PWN emission, and the above-mentioned bent extension of the inner PWN (§ 3.1.2.1) could represent the outer part of the rear jet. Although barely supported by the existing data, the jet hypothesis offers a way to explain the offset large-scale X-ray emission south of the pulsar, which cannot be associated with the shocked pulsar wind under the assumption of wind isotropy. We speculate that this emission could be produced by particles supplied through the front jet (similar to the Vela PWN; Pavlov et al. 2003; Kargaltsev & Pavlov 2004). However, to account for the luminous TeV emission (\( \sim \) just south of the pulsar, which might be interpreted as a part of the shell, and left the high-pressure SNR interiors, which is consistent with the assumption \( p_{\text{amb}} < p_{\text{puls}} \), used to obtain the pulsar velocity estimate. This could explain why J1809 looks so different from those Vela-like PWNe that do not show cometary morphology because they are moving subsonically in high-pressure SNR interiors (see KPG07a for examples). However, if \( \Gamma_{\text{v}} \approx 300(\sin i)^{-1} \) km s\(^{-1}\) and \( \Lambda \approx 25T_4^{-1/2}\mu_{1/2}(\sin i)^{-1/2} \) ergs cm\(^{-2}\) s\(^{-1}\), then the uncertainty of the pulsar’s true age and distance, we cannot rule out the possibility that G11.18+0.01 is the host SNR for J1809.

3.2. The Pulsar

The spectrum of the J1809 pulsar is less certain than that of the PWN. Although the one-component PL model formally fits the spectrum, the fit yields a rather large \( \Gamma \approx 2.6-3.2 \), and suggests a smaller \( n_\| \) than the one obtained from the PL fit to a better quality PWN spectrum. An alternative description of the pulsar spectrum is provided by the two-component PL+BB model that is often used to fit the spectra of young and middle-aged pulsars (see, e.g., KPG07a and references therein). The PL component of the PL+BB fit gives \( \Gamma_{\text{pul}} \approx 1.2 \pm 0.6 \), similar to \( \Gamma_{\text{pwn}} \), and to the spectral slopes of other pulsars of similar ages (see, e.g., KPG07a). In any case, the slope is much softer than the \( \Gamma_{\text{pul}} = (2.1-2.9)E^{-0.1/2}_y \approx 0.1 \) predicted by Gotthelf’s (2003) correlation. The X-ray efficiency of the pulsar, \( \eta_{\text{pul}} = L_{\text{pul}}/E \approx 2 \times 10^{-5} \), is also unusual for Vela-like pulsars, nor is the ratio \( L_{\text{pul}}/L_{\text{pwn}} \approx 10 \) (see KPG07a).

The possible thermal component of the PL+BB fit is poorly constrained, not only because of scarce statistics, but also because the soft thermal radiation is strongly absorbed by the ISM. The BB temperature, \( T \approx 1.7-2.3 \) MK, the emitting area \( A \approx 10^6-10^7 \) m\(^2\), and the bolometric luminosity, \( L_{\text{pul}}^{\text{bol}} \approx (0.6-1.6) \times 10^{37} \) ergs s\(^{-1}\), are similar to those found from the PL+BB fit for Vela-like pulsars. The temperature is a factor of 2 higher than the NS surface temperatures predicted by standard NS cooling models for the 50 kyr age (e.g., Yakovlev & Pethick 2004), and the corresponding emitting area is smaller than the NS surface area. However, the actual spectrum of the NS thermal radiation can differ substantially from the BB model. In particular, fitting the spectra with hydrogen atmosphere models (Pavlov et al. 1995) yields lower effective temperatures and larger emitting areas (see Pavlov et al. 2001b for the specific example of the Vela pulsar). Unfortunately, the quality of the data does not warrant fits with more complicated atmosphere models. Unlike the temperature and the area, the bolometric luminosity is not so sensitive to the presence and properties of the NS atmosphere. A comparison with NS cooling models shows that the J1809’s bolometric luminosity is a factor of \( \sim 10 \) lower than predicted by the “basic” theoretical cooling curve (\( M_{\text{SS}} = 1.3 M_\odot \), no superfluidity); however, it is consistent with the cooling curves for heavier NSs (e.g., \( M_{\text{SS}} = 1.5-1.6 M_\odot \)) for various superfluidity models (Yakovlev & Pethick 2004).

3.3. Host SNR

With the velocity given by equation (2), the pulsar would have traveled a distance of \( \sim 7n^{-1/2}d_4^{-1/3}f_0^2 \sin i \) pc during the time equal to its spin-down age, \( \tau = 51 \) kyr. This corresponds to a displacement of \( \sim 7n^{-1/2}d_4^{-1/3}f_0^2 \sin i \) in the plane of the sky, and, for \( n^{-1/2}d_4^{-1/3}f_0^2 \sin i \approx 0.6 \), places the sky projection of the pulsar’s birthplace close to the center of the radio SNR G11.18+0.11 (see Figs. 4b and 4f), suggesting that J1809 and G11.18+0.11 were created by the same supernova explosion. This conjecture implies that the pulsar has overtaken the SNR shell, and left the high-pressure SNR interiors, which is consistent with the assumption \( p_{\text{amb}} < p_{\text{puls}} \), used to obtain the pulsar velocity estimate. This could explain why J1809 looks so different from those Vela-like PWNe that do not show cometary morphology because they are moving subsonically in high-pressure SNR interiors (see KPG07a for examples). However, if \( G11.18+0.11 \) is at \( d \approx 3.5 \) kpc (the presumed distance to J1809), then its size, \( D \approx 8d_4^3 \) pc, would be surprisingly small for a 50 kyr old SNR, unless it is expanding in an unusually dense environment. To get a more consistent SNR age and size, we have to assume a larger distance and a smaller true age for the pulsar, which would require a lower ambient density around J1809 to match the pulsar’s birthplace with the center of G11.18+0.11, resulting in a higher inferred pulsar velocity and Mach number. For instance, if we assume \( d = 5 \) kpc (i.e., \( D \approx 11 \) pc) and a true age of 20 kyr, then \( n \approx 0.1f_0^4 \sin^4 i \) cm\(^{-3}\) is required, which corresponds to \( \nu \approx 300(\sin i)^{-1} \) km s\(^{-1}\) and \( \Lambda \approx 25T_4^{-1/2}\mu_{1/2}(\sin i)^{-1/2} \) ergs cm\(^{-2}\) s\(^{-1}\). Thus, given the uncertainty of the pulsar’s true age and distance, we cannot rule out the possibility that G11.18+0.01 is the host SNR for J1809.

It is also possible that G11.18+0.01 is just a background SNR accidentally projected near the pulsar. In this case, the real host SNR might be associated with the extended emission around J1809 seen in the Chandra and ASCA images (Fig. 1, bottom right, and Fig. 4c). The faintness of the large-scale X-ray emission does not allow one to determine its origin (thermal or non-thermal), and therefore thermal plasma emission from the SNR interior cannot be excluded until better quality data are obtained (see § 3.2.1). However, the size of this putative SNR is too small, and, more importantly, the observed PWN morphology does not appear consistent with this hypothesis. Therefore, it seems more plausible that the extended emission is synchrotron radiation related to the PWN (see § 3.1.2.2) rather than thermal emission from
hot gas in the SNR interior. Measuring the X-ray spectrum of the extended emission in a deeper observation would distinguish between these possibilities.

One could also speculate that the host SNR is not seen, because its size is larger than the field of view of our observation (≈20 pc at d = 3.5 kpc), and the SNR interior has become cold enough (T \( \lesssim 10^7 \) K) to provide \( M \gg 1 \) and to be undetectable in X-rays. This option remains quite viable if the pulsar’s true age is close to (or exceeds) its spin-down age.

### 3.4. Origin of HESS J1809

TeV radiation can be produced by the inverse Compton scattering (ICS) of low-frequency radiation (e.g., the cosmic microwave background radiation [CMBR]) off relativistic electrons. Alternatively, it can be generated by the \( \pi^0 \rightarrow \gamma + \gamma \) decay, the \( \pi^0 \) mesons being produced when relativistic protons interact with the ambient matter. Therefore, to understand the nature of a TeV source, one should identify the source of the relativistic particles and the target with which these particles interact.

#### 3.4.1. Possible Targets for TeV Radiation Production

The omnipresent target for relativistic electrons producing TeV photons by ICS is the CMBR, with the energy density \( U_{\text{CMBR}} = 0.26 \text{ eV cm}^{-3} \). To produce TeV photons with energy \( E \), by up-scattering the CMBR photons with energy \( \epsilon \sim 3kT \sim 4 \times 10^{-4} \text{ eV} \), electrons with the Lorentz factor \( \gamma \sim 5 \times 10^{11}E_{12}^{1/2} \) (i.e., \( E_\gamma \sim 25E_{12}^{1/2} \text{ TeV} \)) are required, where \( E_{\text{TeV}} = E_\gamma/(1 \text{ TeV}) \). Since \( \gamma \epsilon \sim 20-100 \text{ keV} \ll m_e c^2 \) for \( E_\gamma \sim 1-20 \text{ TeV} \), the ICS occurs in the Thomson regime. The same relativistic electrons produce synchrotron photons with energy

\[
E_{\text{syn}} \sim \gamma^2 \hbar \nu_{\text{cyc}} \sim 5 \gamma^2 B_{-5} \text{ eV} \sim 0.1 \frac{E_{\text{TeV}} B_{-5}}{\epsilon/(4 \times 10^{-4} \text{ eV})} \text{ keV},
\]

where \( \gamma = \gamma/10^7 \), and \( B_{-5} = B/(10 \mu \text{G}) \).

Close to the Galactic plane, where HESS J1809 is situated, a factor of a few higher radiation energy density can be provided by IR emission from interstellar dust and Galactic starlight. For instance, the models of the interstellar radiation field by Strong et al. (2000) give energy densities of 0.6 and 2.7 eV cm\(^{-3}\) for these two components, respectively, at a galactocentric distance of \( \sim 4 \) kpc. Since the ICS proceeds in the Klein-Nishina (K-N) regime for \( \epsilon \gg \gamma E_{\text{TeV}} \) (i.e., the K-N effects become important at \( \epsilon \gg 2 \times 10^{-2} \text{ eV} \) for the high-energy end of the TeV photon spectrum), we should use a more general formula for estimating the electron Lorentz factor:

\[
\gamma \sim \frac{10^8}{E_{\text{TeV}} + \left(E_{\text{TeV}}^2 + E_{\text{TeV}}/\epsilon_{\gamma}\right)^{1/2}}.
\]

where \( \epsilon_{\gamma} = \epsilon/(1 \text{ eV}) \). The electrons with such a Lorentz factor generate synchrotron photons with energy \( E_{\text{syn}} \sim 0.05[E_{\text{TeV}}^2 + (E_{\text{TeV}}^2 + E_{\text{TeV}}/\epsilon_{\gamma})^{1/2}]B_{-5} \) eV. For instance, electrons with \( \gamma \sim 2 \times 10^7 \) (i.e., \( E_\gamma \sim 10 \text{ TeV} \)) produce photons with \( E_\gamma \sim 10 \text{ TeV} \) by up-scattering background starlight photons with a typical energy \( \epsilon \sim 1 \text{ eV} \), and the same electrons produce synchrotron radiation in a far-UV range, \( E_{\text{syn}} \sim 6 \text{ eV} \), in an interstellar field of 3 \( \mu \text{G} \). Although the radiation energy density of the starlight can substantially exceed that of the CMBR, the emissivity is reduced by the smaller Compton cross section in the K-N regime, and the smaller photon number density.

The radiation energy density and photon number density (hence TeV emissivity) can be enhanced in the vicinity of very bright sources. The radiation energy density at an angular distance \( \theta \) from a source of radiation can be estimated as \( U = F/(c\theta^2) \), where \( F \) is the source energy flux observed on Earth; it exceeds the ambient radiation energy density, \( U_{\text{amb}} \), at

\[
\theta < (F/cU_{\text{amb}})^{1/2}.
\]

The multiwavelength data show two very bright radio–IR objects near the center of HESS J1809 source A and source B (see Fig. 4), which are likely molecular/dust complexes in star-forming regions. An approximate integration of the spectral flux of source A gives its total flux \( F_A \sim 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \) (i.e., the luminosity \( L_A \sim 1.5 \times 10^{38}d_{15}^2 \text{ ergs s}^{-1} \)). This means that the radiation energy density near this source exceeds \( U_{\text{amb}} \) at \( \theta < 5'(U_{\text{amb}}/1 \text{ eV cm}^{-3})^{-1/2} \). For instance, if the TeV emission is produced by the ICS of IR photons with energies around \( \epsilon \sim 0.02 \text{ eV} \) (which corresponds to the maximum spectral flux of source A), and \( U_{\text{amb}} \sim 0.1 \text{ eV cm}^{-3} \) in this energy range, then \( U > U_{\text{amb}} \) at \( \theta < 15' \). This value is close to the observed radius of HESS J1809, which suggests that the sphere of \( \sim 10 \) pc of the enhanced radiation field around source A might be the target where the TeV emission is produced by the ICS off the relativistic electrons supplied by a nearby source [Lorentz factors \( \gamma \sim (0.5-6) \times 10^7 \) are required to up-scatter the IR photons to \( E_\gamma = 0.5-20 \text{ TeV} \)]. Similar estimates hold for source B, whose flux is a factor of 2.5 lower, and whose \( \theta \) is a factor of 1.6 smaller, than those of source A. The hypothesis that the “photon sphere” of source A or source B is the site where the TeV emission is produced via ICS could be verified by detection of the accompanying synchrotron radiation. However, most of the energy range of the corresponding synchrotron emission, \( E_{\text{syn}} \sim (1-200)B_{-5} \text{ eV} \), is subject to strong interstellar absorption.

In principle, the TeV emission could be initiated by high-energy nucleons supplied by some source (e.g., a pulsar), which produce decaying \( \pi^0 \) mesons in collisions with nucleons of the ambient medium (e.g., Horns et al. 2007). The target in this case would be the nucleonic component of the circumpulsar medium, and we should expect enhanced TeV emission in dense, cold clouds, if there are such clouds close to the source of high-energy nucleons. The lack of an extended IR or radio counterpart of a size similar to that of HESS J1809 (which would indicate the presence of a large molecular cloud) suggests that the TeV source is not associated with a localized target for high-energy nucleons.

#### 3.4.2. Possible Sources of Relativistic Particles

In the case of HESS J1809, the natural source of relativistic electrons (and possibly protons) is the J1809 pulsar. In addition to that, there are the Ch1 and Ch2 X-ray sources, and the radio SNR G11.03–0.05, which are all projected close to the center of HESS J809 (see Fig. 4). Finally, relativistic particles might be produced by acceleration mechanisms in the forward shock of the putative host SNR of the J1809 pulsar.

The soft X-ray spectrum of Ch2 and the positional coincidence with a field star suggest that the X-ray emission comes from an active stellar corona. Therefore, we conclude that Ch2 is not related to HESS J1809.

If the shell-like radio SNR G11.03–0.05 were a powerful source of relativistic electrons, its synchrotron radiation would have been seen in the X-ray range. Since no X-rays at the SNR location are detected in our Chandra observation, this SNR is not a viable candidate for the source of relativistic particles that powers HESS J1809.

As we have discussed in §§ 3.1.2 and 3.3, the faint, large-scale X-ray emission south of the J1809 pulsar is likely not the
host SNR of this pulsar, but rather related to the J1809 PWN. Moreover, TeV \(\gamma\)-ray emission from an SNR shock is usually associated with the SNR shell, not the interior. Current radio, X-ray, and \(\gamma\)-ray data provide no evidence of such a shell around J1809. Therefore, even if the large-scale X-ray emission belongs to the host SNR, HESS J1809 is unlikely to be powered by particles accelerated in the forward shock of this SNR.

Among the X-ray sources detected with \textit{Chandra}, Ch1 is the closest to the projected HESS J1809 center (Fig. 4). The lack of an IR–optical counterpart, and the large lower limit on the X-ray–to-optical flux ratio, \(F_X/F_{\text{opt}} \gtrsim 3\), mean that the X-ray emission from Ch1 does not come from a typical field star. On the other hand, the absorbing hydrogen column density, \(n_H \approx 1.2 \pm 0.4\), is close to that of the J1809 PWN, which suggests that Ch1 is a Galactic object, not an AGN observed through the Galactic plane. The slope of the Ch1 spectrum, \(\Gamma = 1.4 \pm 0.4\), suggests that it may be either an X-ray binary or a remote PWN that is unresolved because of its far off-axis location. With the optical extinction estimated from the measured \(n_H\) value (e.g., \(A_V \sim 4-9\)), the limits on the optical–NIR magnitudes (see \S 2.5) virtually exclude a high-mass X-ray binary. Although a low-mass X-ray binary (LMXB) in a quiescent state could have an X-ray luminosity comparable to that of Ch1, \(L_{\text{Ch1}} \sim 3 \times 10^{37}$ (\(d/4\) kpc)\(^2\) ergs s\(^{-1}\)), LMXBs are not known to be sources of TeV emission. If Ch1 is a young pulsar with a PWN, then it might provide the relativistic particles needed for generating the TeV emission. (We should note, however, that the TeV-to-X-ray flux ratio, \(~\sim 150\), would be much higher than the values, \(~0.01-3\), inferred for most of the other TeV PWNs, except for the B1800–21, for which the ratio is about 100; see Table 2 in Kargaltsev et al. [2007b], hereafter KPG07b, and references therein). To assess the likelihood that Ch1 is the source of relativistic particles for HESS J1809, a deeper \textit{Chandra} observation is needed, with Ch1 imaged close to the telescope’s optical axis.

Another plausible physical counterpart to HESS J1809 is the J1809 pulsar/PWN. To date, young pulsars have been found in the vicinity of \(~\sim 10\) extended TeV sources (e.g., de Jager et al. 2006; Gallant 2007), and the likelihood of this happening by chance is very low (see, e.g., KPG07b). The ratio of the TeV flux of HESS J1809 to the X-ray flux of the J1809 PWN (including the outer component of the compact PWN) is about 50, higher than that observed in most TeV pulsars (KPG07b). However, if one adds in the X-ray flux of the large-scale extended emission (\S 2.2.1), then the ratio decreases down to \(~\sim 10\) (or even lower if one includes the diffuse emission of a larger extent, seen by ASCA; see Fig. 4c).

The center of HESS J1809 is offset from J1809 by \(~\sim 8\)′, almost in the direction of the presumed pulsar motion. Such an offset is comparable to the \(~\sim 20\)′ offsets found in most TeV pulsars (including the most secure associations, PSR B0833–45/HESS J0835–455 [Vela] and PSR B1823–13/HESS J1825–137). An obvious explanation for such an offset is that the photons for the ICS are provided by a compact source (e.g., source A) whose center lies at some distance from the pulsar (\(~\geq 8d_{3.5}\) pc for source A). Also, the offset might be due to the anisotropic supply of relativistic particles through the putative front jet (see \S 3.1.2).

If the TeV emission is produced by the ICS of an approximately uniform background radiation, such as the CMBR or Galactic starlight, then the origin of the offsets and the asymmetries of the extended X-ray and TeV PWN components could be attributed to a reverse SNR shock that had propagated through the nonhomogeneous SNR interior, and reached one side of the PWN sooner than the other side, crushing the PWN, and sweeping its contents along (Blondin et al. 2001). One can assume that the TeV source HESS J1809 is powered by this relic crushed PWN, whose relativistic electrons have not lost all their energy to synchrotron radiation because of, e.g., a lower magnetic field, while the compact PWN in the pulsar vicinity is created by fresh electrons, recently injected from the pulsar’s magnetosphere. As the electrons responsible for the TeV emission would have been accumulating during a substantial fraction of the pulsar’s lifetime, and the pulsar’s spin-down power was higher in the past, this hypothesis could explain the uncomfortably large ratio, \(~\sim 0.01d_{3.5}^3\), of the TeV luminosity to the current spin-down power. (A similar explanation has been suggested by Aharonian et al. [2006] for the PSR B1823–13/HESS J1825–137 association.) This hypothesis can be tested with deep radio observations, which should be able to detect the synchrotron emission from the relic electrons of the crushed PWN.

In the above picture, the asymmetric extended X-ray emission south of the J1809 pulsar could also be associated with the crushed PWN, and considered as an X-ray (synchrotron) counterpart of the TeV (IC) source HESS J1809. The small size of the extended X-ray emission, in comparison with the size of the TeV source, and its offset from the center of HESS J1809 could be attributed to the lower sensitivity of the ACIS-S2 chip (where the central part of HESS J1809 is imaged; see Fig. 4a) or to a lower magnetic field in the central part. A deeper X-ray observation could distinguish between these two possibilities.

The large-scale morphology of the X-ray emission around J1809 is remarkably similar to that around PSR B1823–13, which powers the X-ray PWN G18.0–0.7 (\(<L_X \sim 3 \times 10^{37}$ ergs s\(^{-1}\); angular size \(~\gtrsim 5\); Gaensler et al. 2003). In addition to the extended low-surface-brightness component, the B1823–13 PWN has a much more compact \((5''-10'')\), brighter core, resolved by \textit{Chandra} (Teter et al. 2003; Pavlov et al. 2007). The TeV emission from HESS 1825–137 covers an area much larger than the X-ray PWN area, extending up to 1′ southward from the pulsar (Aharonian et al. 2006). However, just as in the case of PSR J1809/HESS J1809, the TeV and the low-surface-brightness X-ray emission have similar shapes, and they are offset in the same direction with respect to the pulsar position.

Finally, we would like to point out that there are two other young pulsars, J1811–1925 and J1809–1943, at distances of \(~\sim 24′\) and \(~\sim 19′\), respectively, from the HESS J1809 center. PSR J1811–1925 cannot be related to HESS J1809, since it has been associated with G11.2–0.3 (Kaspi et al. 2001), whose diameter, \(~\sim 4′\), is substantially smaller than the offset from HESS J1809. PSR J1809–1943 is the radio counterpart of the transient anomalous X-ray pulsar (AXP) XTE J1810–197 (Camilo et al. 2006, and references therein). Its association with HESS J1809 does not look very plausible, because of its large spatial offset, and because its properties are quite different from those of the young pulsars found in the vicinity of other TeV sources (no TeV emission from AXPs have been reported so far).

Thus, based on the current data, only two objects, the J1809 pulsar/PWN and, less likely, Ch1, are plausible candidates for the source of relativistic particles powering HESS J1809. In both cases, the TeV emission is generated by ICS of either IR photons from source A (or source B) or CMBR photons. To discriminate between different possibilities, the nature of Ch1 should be established in deep, high-resolution \textit{Chandra} observations, and the extended X-ray PWN emission should be studied in a deep \textit{XMM-Newton} exposure. The synchrotron emission from the alleged relic PWN could be detected in deep radio observations.

4. CONCLUSION

We have detected the X-ray emission from PSR J1809–1917 and its synchrotron nebula. The X-ray efficiency and spectrum
of the PWN are similar to those of many other compact PWNe, both younger and older than J1809. The cometary shape of the compact PWN suggests that the pulsar is moving supersonically, but no extended tail has been detected behind the pulsar, perhaps because the Mach number is not large enough, or the exposure time is too short. Our analysis of the PWN morphology suggests an anisotropic pulsar wind outflow, possibly including jets oriented along the direction of pulsar motion. To establish the nature of the compact PWN unambiguously, proper motion measurements and a deeper Chandra observation are required.

The compact PWN is immersed in an extended emission of lower surface brightness. This extended emission is offset with respect to the pulsar in the direction opposite to that of the compact PWN (i.e., in the direction of the alleged proper motion). If the extended emission is indeed powered by the supersonically moving pulsar, then the radiating particles could be supplied through the front jet of the compact PWN, or brought by the northern part of the reverse SNR shock that overtook the pulsar moving southward.

The spectrum of the pulsar can be described by a two-component PL+BB model. For reasonable $n_H$ values, the parameters of this model and the corresponding component luminosities resemble those of Vela-like pulsars.

The J1809 pulsar and its PWN are located in the vicinity of the unidentified extended TeV source HESS J1809–93, which can be powered by ultrarelativistic electrons in the vicinity of the J1809 PWN. In addition to J1809, we found another X-ray source, Ch1, within the central part of HESS J1809, which might also be an unresolved pulsar/PWN. Although the true nature of Ch1 remains elusive, we cannot rule out the possibility that Ch1 is an alternative X-ray counterpart of HESS J1809. Regardless of which of the two objects, J1809 or Ch1, supplies the relativistic electrons, the TeV emission is likely produced by the ICS of either CMBR or IR photons from bright $IRAS$ sources (source A or source B) projected near HESS J1809.

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