Discovery of a Pulsar Candidate Associated with the TeV Gamma-ray Source HESS J1813–178

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Abstract.
We present a Chandra X-ray observation of G12.82–0.02, a shell-like radio supernova remnant coincident with the TeV gamma-ray source HESS J1813–178. We resolve the X-ray emission from the co-located ASCA source into a compact object surrounded by structured diffuse emission that fills the interior of the radio shell. The morphology of the diffuse emission strongly resembles that of a pulsar wind nebula. The spectrum of the compact source is well-characterized by a power-law with index $\Gamma \approx 1.3$, typical of young and energetic rotation-powered pulsars. For a distance of 4.5 kpc, consistent with the X-ray absorption, the 2–10 keV X-ray luminosity of the putative pulsar and nebula is $L_{\text{PWN}} = 3.2 \times 10^{33}$ erg s$^{-1}$ and $L_{\text{PFR}} = 1.4 \times 10^{34}$ erg s$^{-1}$, respectively. Both the flux ratio of $L_{\text{PWN}}/L_{\text{PFR}} = 4.3$ and the total luminosity of this system imply a pulsar spin-down power of $\dot{E} > 10^{37}$ erg s$^{-1}$, on a par with the top ten most energetic young pulsars in the Galaxy. We associate the putative pulsar with the radio remnant and the TeV source and discuss the origin of the $\gamma$-ray emission.

Keywords: stars: individual (CXOU J181335.17–174957.4, G12.82–0.02) — ISM: supernova remnant — stars: neutron — X-rays: stars — pulsars: general
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INTRODUCTION

The HESS observatory has opened an important new window onto the highest energy astrophysical processes ($> 10^{11}$ eV $= 0.1$ TeV) with unprecedented sensitivity and spatial resolution [1]. Of the 22 Galactic TeV sources detected by HESS over the first two years of four-telescope operation, nearly half are associated with supernova products – supernova remnants (SNRs) or pulsar wind nebulae (PWNe) [2, 12]. With the exception of two associations with binary systems, the remainder have yet to be identified with a known source at any other wavelength. The growing number of supernova products associated HESS sources provide a unique opportunity to locate new examples of these objects and to determine the mechanism(s) for generating their $\gamma$-ray photons.

In this paper we focus on G12.82–0.02, the first case of a SNR located by its TeV emission [4, 9]. This previously uncatalogued faint shell-type radio supernova remnant (diameter $\sim 2\prime$) lies within the error circle of the unidentified source HESS J1813–178 [1, 2, 11]. It was soon found to be coincident with an unpublished non-thermal 2–10 keV ASCA X-ray source [4, 9], a 10–100 keV INTEGRAL hard X-ray source [15], and a 0.4–10 TeV MAGIC $\gamma$-ray detection [3]. Based on a recent follow-up XMM-Newton X-ray observation, the 2–10 keV X-ray morphology suggests a composite remnant interacting with ambient material to produce the TeV emission [13].

Herein we report on a high-resolution X-ray imaging observation of G12.82–0.02 obtained with the Chandra Observatory. This new data allows us to associate this remnant with a young, energetic rotation-powered pulsar generating a bright wind nebula, ultimately responsible for the TeV emission from HESS J1813–178. In the following we use a distance to G12.82–0.02 of $d = 4.5$ kpc as suggested by Helfand et al. [10].

THE CHANDRA X-RAY OBSERVATION OF SNR G12.82–0.02

A 30 ks X-ray observation of SNR G12.82–0.02 was obtained on 2006 Sept 15 UT using the Chandra X-ray observatory (see Helfand et al. [10] for a full description of this observation). Data were collected with the Advanced CCD Imaging Spectrometer (ACIS) in the focal plane, operating in the nominal full-frame TIMED/VFAINT exposure mode. The coordinates of the ASCA source associated with G12.82–0.02 were positioned on the ACIS-I3 CCD chip and offset by 2$\prime$ from the nominal aimpoint to allow any extended X-ray emission from the source to fall wholly on this chip. A total of 29.6 ks of live-time was accumulated with a CCD frame time of 3.241 s (1.3% deadtime). We used the pipeline level 2 event products and reduced and analyzed this data using the standard X-ray analysis software.

As shown in Figure 1, the Chandra ACIS image of G12.82–0.02, with a near on-axis spatial resolution of $\approx 0.5$, fully resolves the ASCA source into diffuse X-ray emission and a point source. The diffuse flux generally fills in the...
radio shell and peaks toward the point source emission, located at RA = 18:13:35.17, Dec = -17:49:57.48 (J2000; 1σ error radius of ≈ 0'0.2). These coordinates were determined after registering the image using nine X-ray field stars with USNO-B1 optical counterparts, and lies less than 1' from the maximum probability centroid of HESS J1813−178, well within its 2'2 (1σ) extent.

The point source is clearly offset from the center of the nearly symmetric radio remnant, by 20''. This suggests either rapid source motion or asymmetric SNR expansion relative to a common birth center. Extending west/southwest of the source is a faint localized loop of emission not clearly resolved (Figure 1, middle plot). A radial profile centered on the point source shows that this excess emission is prominent out to 5'' and disappears into the background at about 10''. The profile of the point emission is consistent with the mirror response function when the large-scale diffuse flux is taken into account. No obvious evidence is found for any X-ray structure corresponding to the radio shell.

To further study the nature of the X-ray emission from G12.82−0.02 we extracted spectra from the point source, the diffuse nebula, and the faint inner nebula, and from appropriate background regions. A total of 864 photons were collected from a 2'' radius aperture centered on CXOU J181335.17−174957.4; this included 19 background counts, estimated from the local diffuse emission. Because of the low count rates involved, photon pile-up is negligible. To encompass the bulk of the nebula, we define an 80''-radius region, centered on the remnant, with the point source and inner nebula regions excluded (see below); a total of 6638 photons were obtained. The background for this spectrum was extracted from a 56''-radius circle offset due north of the nebula region and contained 1363 counts. For the inner nebula we use a 6''× 8'' elliptical extraction region tilted with a position angle of 240° with the point source excluded. After accounting for the local background (28%) this resulted in a total of 223 photons.

Spectra from each region were grouped for a minimum of 15 cts per spectral channel and fitted using the XSPEC software in the 2−10 keV energy band, below which the line-of-sight flux is evidently highly absorbed. These CCD spectra (∆E/E ~ 0.06 FWHM at 1 keV) are all well-characterized (but not uniquely) by an absorbed power-law model associated with non-thermal emission. For the nebula flux, the best-fit photon index is Γ = 1.3(1.1,1.6), averaged over this region, with an NH = 9.8(8.7−11) × 10^{22} cm^{-2}, consistent with that derived from NANTEN 12CO(J=1−0) measurements [11]. In fitting the putative pulsar the column density was fixed to the value derived for the higher-significance nebula spectrum. The best-fit model yields a surprisingly similar index, Γ = 1.3^{+0.6}_{−0.0}, not unlike that found for the Vela pulsar, and to be expected for the most energetic rotation-powered pulsars (cf. Gotthelf [12]). The absorbed 2−10 keV fluxes for the putative pulsar (PSR) and PWN are F_{PSR} = 1.3 × 10^{-12} erg cm^{-2} s^{-1} and F_{PWN} = 5.6 × 10^{-12} erg cm^{-2} s^{-1}, respectively. These results are consistent with the ASCA measurements of the composite spectrum and, as discussed below, have important implications for the energetics of the system. The spectral distribution of the inner nebula (IN) photons is not well-constrained, but a fit with the power-law model yields a somewhat flatter index of Γ = 0.4^{+0.6}_{−0.3} than that of the PWN, with a flux of F_{IN} ~ 4 × 10^{-13} erg cm^{-2} s^{-1}. Significantly, no emission line features are found in any of the spectra analyzed.
DISCUSSION

The Chandra results offer a compelling case that the high-energy emission from G12.82–0.02 is derived from the spin-down energy of a young rotation-powered pulsar. Deep radio pulsar searches, however, have so far failed to detect a signal from CXOU J181335.17−174957.4 to an upper-limit that approaches those measured for the least luminous young pulsars. Nor have searches for slow periodicity using the X-ray data produced evidence of a signal, although these results are not very constraining, with a 3σ upper-limit for a sinusoidal modulation of 44% for ASCA (P > 125 ms), 27% for ACIS (P > 6.5 s), and 100% for XMM-Newton (P > 147 ms) [4, 10]. More significant timing searches are needed to verify our pulsar hypothesis for G12.82–0.02. A detection will allow a search for pulsed γ-rays with the GLAST mission. Together, these results will help fully quantify the energetics of this system.

That the putative pulsar is highly energetic is manifest by the large flux ratio of \( F_{\text{PWN}} / F_{\text{PSR}} = 4.3 \) in the 2–10 keV energy band; only rotation-powered pulsars with spin-down energy loss rates above \( \dot{E} \approx 4 \times 10^{36} \text{ erg s}^{-1} \) have a ratio this large or greater [7]. Furthermore, the total 2–10 keV luminosity of \( L_X = 1.74 \times 10^{34} d_{15}^2 \text{ erg s}^{-1} \) from G12.82–0.02 corresponds to \( \dot{E} \approx 10^{37} \text{ erg s}^{-1} \) [11], placing this object among the Galaxy’s top ten most energetic pulsars. In particular, G12.82–0.02 bears a striking similarity in many respects to SNR G106.6+2.9, a radio remnant undetected in X-rays that contains the energetic pulsar PSR J2229+6114 with \( \dot{E} = 1.8 \times 10^{37} \text{ erg s}^{-1} \) and flux ratio of \( F_{\text{PWN}} / F_{\text{PSR}} = 9 \) [8].

The nature of the inner nebula resolved by the Chandra data is not yet clear. If we assume that the pulsar’s velocity vector is away from the SNR center, it is hard to reconcile this feature with a bow-shock origin. As a torus, it is unusually asymmetric and not well centered on the pulsar. The relation between this feature and that of the greater nebula requires a deeper Chandra observation to consider further.

The TeV emission from HESS J1813−178 is also likely to be also powered, ultimately, by the putative pulsar. The spatially coincident X-ray and TeV emission is notably rare among the molecular cloud, as suggested by Yamazaki et al. [16]. The TeV photons in this latter scenario arise from “relic” electrons injected at an earlier epoch [6]. The vector is away from the SNR center, it is hard to reconcile this feature with a bow-shock origin. As a torus, it requires a deeper observation to consider further.

A more plausible explanation for the TeV emission from G12.82–0.02 is inverse-Compton scattering of ambient photons off relativistic electrons accelerated by the pulsar wind. Indeed, the remnant’s broadband spectrum (combining radio, X-ray, and INTEGRAL, and HESS data) is well-fitted using the inverse-Compton model, although a large photon field (1000 eV cm\(^{-3}\)) is required [13]. The nearby HII region W33 may provides a significant local infrared photon flux, but it is unlikely to reach the necessary photon density [9]. Given that several TeV detected PWNe lie near star-formation regions, they may ultimately prove important for generating the TeV emission [10]. Future GLAST observation will be critical for constraining possible spectral models and addressing these issues.

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