DISCOVERY OF A HIGHLY ENERGETIC X-RAY PULSAR POWERING HESS J1813−178 IN THE YOUNG SUPERNova REMnant G12.82−0.02

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ABSTRACT

We report the discovery of 44.7 ms pulsations from the X-ray source CXOU J181335.1−174957 using data obtained with the XMM-Newton Observatory. PSR J1813−1749 lies near the center of the young radio supernova remnant G12.82−0.02, which overlaps the compact TeV source HESS J1813−178. This rotation-powered pulsar is the second most energetic in the Galaxy, with a spin-down luminosity of $E = (6.8 \pm 2.7) \times 10^{37}$ erg s$^{-1}$. In the rotating dipole model, the surface dipole magnetic field strength is $B_s = (2.7 \pm 0.6) \times 10^{12}$ G and the spin-down age $\tau_e \equiv P/2\dot{P} = 3.3−7.5$ kyr, consistent with the location in the small, shell-type radio remnant. At an assumed distance of 4.7 kpc by association with an adjacent young stellar cluster, the efficiency of PSR J1813−1749 in converting spin-down luminosity to radiation is $\approx 0.03\%$ for its 2–10 keV INTEGRAL flux, $\approx 0.1\%$ for its 20–100 keV INTEGRAL flux, and $\approx 0.07\%$ for the $>200$ GeV emission of HESS J1813−178, making it a likely power source for the latter. The nearby young stellar cluster is possibly the birthplace of the pulsar progenitor, as well as an additional source of seed photons for inverse Compton scattering to TeV energies.

Key words: ISM: individual (HESS J1813−178, G12.82−0.02) – pulsars: individual (PSR J1813−1749) – supernova remnants

1. INTRODUCTION

The identification of high-energy (TeV) $\gamma$-ray emission in our Galaxy with supernova products has opened up new prospects for understanding the energetics of these stellar remnants. Over half of the >50 Galactic TeV sources are identified with supernova remnants (SNRs) or pulsar wind nebulae (PWNe). Several physical mechanisms are available for generating the observed $\gamma$-ray photons, including nonthermal bremsstrahlung, and inverse Compton scattering of ambient microwave, infrared (IR), or optical photons off relativistic electrons. $\gamma$-rays can also be produced in hadronic collisions of high-energy protons off local material, from the decay of their neutral pion products. An unambiguous detection of the latter process associated with a Galactic SNR would provide direct confirmation of cosmic-ray production in SNR shocks.

A unique opportunity to explore these high-energy mechanisms is provided by the TeV source HESS J1813−178, one of the brightest and most compact objects located by the HESS Galactic Plane Survey (Aharonian et al. 2005a). Within the TeV extent lies G12.82−0.02, a previously uncataloged young shell-type radio SNR (Brogan et al. 2005; Helfand et al. 2005). Furthermore, there is evidence for broadband high-energy emission. Overlapping the SNR shell lies a 2−10 keV X-ray source AX J1813−178 (Brogan et al. 2005; Helfand et al. 2005), the INTEGRAL soft gamma-ray (20−100 keV) source IGR J18135−1751 (Ubertini et al. 2005), and possibly GeV emission from the Fermi source 0FGL J1814.3−1739 (Abdo et al. 2009). Follow-up high-resolution X-ray studies resolved the X-ray emission into a point source and bright surrounding nebula, whose properties indicate that a young, energetic rotation-powered pulsar (Funk et al. 2007; Helfand et al. 2007) is responsible for the extended X-ray emission and, ultimately, the broadband high-energy radiation. A deep radio timing search failed to detect pulsations (Helfand et al. 2007).

In this Letter, we report on a long, continuous XMM-Newton X-ray timing observation of CXOU J181335.1−174957, the central point source in G12.82−0.02, resulting in the discovery of PSR J1813−1749. We show that the spin-down luminosity of the pulsar is sufficient to power the broadband X-ray and $\gamma$-ray emission. A nearby young stellar cluster (Messineo et al. 2008) may provide seed photons for upscattering to $\gamma$-rays, and is a possible birth place of the pulsar progenitor.

2. XMM-NEWTON OBSERVATIONS AND RESULTS

The Chandra source CXOU J181335.1−174957 was observed by XMM-Newton with a 98 ks exposure on 2009 March 27 using the European Photon Imaging Camera (EPIC; Turner et al. 2003). The EPIC pn CCD was operated in small-window mode ($4'\times 4'$ field of view; 29% dead time). This mode provides 5.7 ms time resolution, allowing a search for even the most rapidly rotating young pulsar. XMM-Newton is sensitive to X-rays in the nominal 0.1−12 keV range with energy resolution $\Delta E/E \approx 0.1/\sqrt{E}$ (keV). The target was placed at the default EPIC pn focal plane location for a point source. Data were also acquired with the two EPIC MOS CCD cameras (MOS1 and MOS2). These were operated in full frame mode with a time resolution of 2.6 s, insufficient to search for a typical pulsar signal. The medium filter was used for both EPIC instruments.

All data were processed using the SAS version xmmmsas_20060628_1801-7.0.0 pipeline, and were analyzed using both the SAS and FTOOLS software packages. The observation was free of significant particle contamination and provided a near continuous 97.9 ks of good observing time per detector. Photon arrival times from the pn CCD were transformed to the solar system barycenter in Barycentric Dynamical Time (TDB) using the JPL DE200 ephemeris and the Chandra measured coordinates given in Helfand et al. (2007).

To search for the expected pulsed signal in the pn CCD, 2−10 keV photons were extracted from an 0.5 diameter aperture centered on the source, optimized for the highly absorbed point source embedded in the substantial nebular emission (see...
Helfand et al. 2007). A 225-bin fast Fourier transform (FFT) search algorithm was used and a highly significant signal was detected at \( P = 44.7 \) ms. We performed a refined \( Z^2_I \) (Rayleigh) search (Buccheri et al. 1983) centered on the FFT signal and localized the pulsed emission with peak power \( Z^2_I = 476 \). This corresponds to essentially zero false detection probability for the number of independent search trials. The pulse profile is slightly narrower than a sinusoid and shows no energy dependence in subdivided bands within the 2–10 keV range.

Given the long time span of the data, we also looked for the effect of a period derivative \( \dot{f} \) on the pulsar signal by constructing a \( Z^2_I \) search over \((f, \dot{f})\) space. Figure 1 shows the resulting contours for the signal power at the 68%, 90%, and 95% confidence level for two interesting parameters. The formal result is \( f = 22.371716(2) \) Hz and \( \dot{f} = -0.773 \pm 0.032 \times 10^{-11} \) Hz \( s^{-1} \); the uncertainties are 1\( \sigma \). This large \( \dot{f} \) is detectable in the single long observation, as the quadratic term \( \frac{1}{2} \dot{f} (t - t_0)^2 \) in the phase ephemeris contributes \(-0.37\) cycles of rotation over the elapsed time. However, its value is highly uncertain at the 95% confidence level, as shown in Figure 1. A precise value of \( \dot{f} \) will be determined easily with a follow-up observation. The best value and 1\( \sigma \) range for the spin-down parameters in the dipole pulsar model are spin-down power \( E \equiv -4\pi^2 I f \dot{f} = (6.8 \pm 2.7) \times 10^{37} \) erg \( s^{-1} \), surface dipole magnetic field strength \( B_s \equiv 3.2 \times 10^{19} \sqrt{-f / \dot{f}^2} = (2.7 \pm 0.6) \times 10^{12} \) G, and characteristic age \( \tau_c \equiv -f / 2 \dot{f} = 3.3\)–7.5 kyr. The pulsar parameters are listed in Table 1.

Figure 2 presents the pulse profile of PSR J1813–1749 corresponding to the data folded at the peak signal value in \((f, \dot{f})\) space. The detected pulsed fraction for the extracted photons is 25\% ± 3\%, defined here as \( N(\text{pulsed})/N(\text{total}) \), where we choose the minimum of the folded light curves as the unpulsed level. The quoted uncertainties are derived by propagating the counting statistics of the light curve for 10 bins.

The intrinsic pulsed fraction is difficult to determine due to the background contamination from the PWN in the source aperture. The intrinsic pulsed fraction is difficult to determine due to the background contamination from the PWN in the source aperture.

| Parameter | Value |
|-----------|-------|
| R.A. (J2000) \(^a\) | 18h13m35s |
| Decl. (J2000) \(^a\) | −17°49’57”’48 |
| Epoch (MJD) | 54917 |
| Period, \( P \) (ms) | 44.699297(4) |
| Period derivative, \( \dot{P} \) | \((1.5 \pm 0.6) \times 10^{-13}\) |
| Characteristic age, \( \tau_c \) (kyr) | 3.3–7.5 |
| Spin-down luminosity, \( E \) (erg s\(^{-1}\)) | \((6.8 \pm 2.7) \times 10^{37}\) |
| Surface dipole magnetic field, \( B_s \) (G) | \((2.7 \pm 0.6) \times 10^{12}\) |

Notes. 1\( \sigma \) uncertainties are given.

\(^a\) Chandra ACIS-I position from Helfand et al. (2007).

3. DISCUSSION

3.1. Age and Energetics

HESS J1813–178 is one of the more compact TeV sources to be associated with an SNR. The Gaussian extent of the source is only \( \sigma = 2.2 \pm 0.4 \) (Aharonian et al. 2006a), while the radio shell of G12.82–0.02 is only 2.5 in diameter (Brogan et al. 2005). It is not clear if these are significantly different. Unlike PSR J1813–1749/HESS J1813–178, many TeV sources associated with pulsars show a notable displacement between the two, e.g., PSR B0833–45/Vela X (Aharonian et al. 2006b), PSR B1823–13/HESS J1825–137 (Aharonian et al. 2006c; Pavlov...
et al. 2006a; Landi et al. 2007). For these systems, the TeV emission may be significantly smaller than this because its initial period may be as small as 300 yr if it is still in the free-expansion stage. In these relatively young and compact PWNe, the high-energy (inverse Compton) TeV emission. The Crab, PSR J1833−1917 shares with these young pulsars a characteristic age \( \leq 5000 \) yr, but its true age may be significantly smaller than this because its initial period \( P_0 \) is not necessarily \( \ll P \). In fact, Brogan et al. (2005) estimate an age of \( \sim 2500 \) yr for PSR J1842−02 near a young stellar cluster of Messineo et al. (2008) are seen to the southwest (dashed circle).

their X-ray luminosities by a large factor, which is observed for several sources.

In the case of PSR J1813−1749/HESS J1813−178, the compact TeV source and lack of relative offset can now be explained by its youth, such as the Crab and several young pulsars with compact HESS sources that are co-located with their X-ray PWNe. The other compact sources are PSR J1846−0258/HESS J1846−029 in the SNR Kes 75 (Djannati-Ataï et al. 2008), PSR J1833−1034/HESS J1833−105 in G21.5−0.9 (Djannati-Ataï et al. 2008), and the newly discovered 52 ms pulsar J1747−2809/HESS J1747−281 in G0.9+0.1 (Camilo et al. 2009; Aharonian et al. 2005b). PSR J1846−0258 is a 0.325 s pulsar with a characteristic age \( \tau_c \) of only 728 yr, and a spin-down luminosity \( E = 8 \times 10^{36} \) erg s\(^{-1}\) (Gotthelf et al. 2000). PSR J1833−1034 has \( \tau_c = 4900 \) yr and \( E = 3.3 \times 10^{37} \) erg s\(^{-1}\). However, the actual age of PSR J1833−1034 is probably only \( \sim 870 \) yr as measured by the expansion of G21.5−0.9 (Bietenholz & Bartel 2008). PSR J1747−2809 has \( E = 4.3 \times 10^{37} \) erg s\(^{-1}\) and \( \tau_c = 5300 \) yr. PSR J1813−1749 shares with these young pulsars a characteristic age \( \leq 5000 \) yr, but its true age may be significantly smaller than this because its initial period \( P_0 \) is not necessarily \( \ll P \). In fact, Brogan et al. (2005) estimate an age of \( \sim 2500 \) yr for PSR J1842−02 near a young stellar cluster of Messineo et al. (2008) are seen to the southwest (dashed circle).

3.2. Environment and Associations

The location of G12.82−0.02 near a young stellar cluster rich in massive binaries and containing a second SNR (G12.72−0.00) suggests an association (Messineo et al. 2008). Those authors determined cluster membership for giants and early-type stars, and derived a consistent distance of 4.7 kpc using radial velocities and optical/IR extinction. They estimated an age of 6–8 Myr, and a total initial cluster mass of...
2000–6500 $M_\odot$. It is plausible that the progenitors of both G12.82−0.02 and G12.72−0.00 were born in the cluster, and had masses similar to those of the red supergiant and WR stars now present, 20–30 $M_\odot$. The cluster is centered 4.4 southwest of G12.82−0.02 (see Figure 3). At this offset, a 5 kyr old neutron star born in the center of the cluster requires a transverse velocity of ≈1200 km s$^{-1}$ to reach its present location, or less if it was born in the outskirts close to its present location.

It is plausible that seed IR/optical photons from this star cluster enhance TeV emission from HESS J1813−178, via inverse Compton scattering in its extended PWN, above the minimum expected from the cosmic microwave background. Such a role was also hypothesized by Helfand et al. (2007) for the adjacent W33 star-forming region, at an estimated distance of 4.3 kpc. Although these objects are not necessarily all at the same distance, they could be.

Pulsed emission from PSR J1813−1749 is expected to be detectable by Fermi, and the GeV band could be where the luminosity peaks, as it does in many energetic pulsars. Although a possible association of the Fermi source 0FGL J1814.3−1739 with HESS J1813−178/G12.82−0.02 has been noted by Abdo et al. (2009), the SNR lies just outside the large, 11′ radius 95% confidence Fermi error circle. It is not yet possible to identify definitively the GeV emission with the pulsar, which would require detection of pulsed γ-rays. The implied luminosity of 0FGL J1814.3−1739 (assumed isotropic) in Table 2 is consistent with the trend of efficiencies among γ-ray pulsars (Thompson 2004). Accumulation of more exposure with Fermi and detailed investigation of this region could be informative.

4. CONCLUSIONS

Using XMM-Newton, we discovered PSR J1813−1749, a highly energetic 44.7 ms pulsar associated with the SNR G12.82−0.02 and powering its PWN from X-ray to TeV energies. Its preliminary spin-down properties make it one of the most energetic pulsars in the Galaxy, possibly second only to the most energetic pulsars in the Galaxy, possibly second only to the Crab. Its apparent youth explains the small extent of its SNR and TeV nebula relative to older pulsars. The high E and young age support a one-zone synchrotron/IC model of the type applied by Funk et al. (2007), in which PSR J1813−1749 accelerates electrons to >10$^{15}$ eV. The lack of an X-ray SNR shell, coupled with a high spin-down power for PSR J1813−1749, argues that the PWN, not the SNR, is almost certainly the TeV source.

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