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PSR J1856+0245: ARECIBO DISCOVERY OF A YOUNG, ENERGETIC PULSAR COINCIDENT WITH THE TeV γ-RAY SOURCE HESS J1857+026

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ABSTRACT

We present the discovery of the Vela-like radio pulsar J1856+0245 in the Arecibo PALFA survey. PSR J1856+0245 has a spin period of 81 ms, a characteristic age of 21 kyr, and a spin-down luminosity $\dot{E} = 4.6 \times 10^{36}$ ergs s^{-1}. It is positionally coincident with the TeV γ-ray source HESS J1857+026, which has no other known counterparts. Young, energetic pulsars create wind nebulae, and more than a dozen pulsar wind nebulae have been associated with very high energy (100 GeV–100 TeV) γ-ray sources discovered with the HESS telescope. The γ-ray emission seen from HESS J1857+026 is potentially produced by a pulsar wind nebula powered by PSR J1856+0245; faint X-ray emission detected by *ASCA* at the pulsar's position supports this hypothesis. The inferred γ-ray efficiency is $\epsilon_\gamma = L_\gamma / \dot{E} = 3.1$ % (1–10 TeV, for a distance of 9 kpc), comparable to that observed in similar associations.

Subject headings: gamma rays: observations — pulsars: general — pulsars: individual (PSR J1856+0245) — stars: neutron — X-rays: individual (AX J185651+0245)

1. INTRODUCTION

In the last few years, approximately 40 new Galactic sources of very high energy (VHE) γ-ray emission (100 GeV–100 TeV) have been discovered using the High Energy Stereoscopic System (HESS[18]) Cerenkov telescope array (e.g., Aharonian et al. 2005a). These are an exciting new population of sources, which give new insight into nonthermal particle acceleration in Galactic objects such as neutron stars, supernova remnants, and X-ray binaries. Thus far, close to half of these sources have been established or suggested as being associated with the pulsar wind nebulae (PWNe) of young pulsars, either through direct detection of a PWN or positional coincidence with a young pulsar which is presumed to have a PWN (Table 1). Clearly, PWNe are now an important and well-established Galactic source of VHE γ-rays. Since both young pulsars and their PWNe can be very dim, many of the Galactic HESS sources without identified counterparts (e.g., Aharonian et al. 2008b) may be PWNe, potentially detectable via deep radio or X-ray observations.

In general, radio/X-ray PWNe are associated with extended HESS sources, presumably TeV PWNe, whose peak is offset by several arcminutes from the pulsar[19] (Table 1). In some cases the offset, if any, cannot be measured because the position of the pulsar is not known (see also Gallant 2007). These offsets have been explained by the hypothesis that the VHE emission is from inverse Compton scattering of "old" electrons, which were produced during an earlier epoch in the pulsar's life, off of the ambient photon field (e.g., cosmic microwave background radiation, starlight, and infrared emission from dust; see Aharonian et al. 2005d; de Jager & Djannati-Ataï 2008). An alternative model has the γ-rays produced by the decay of π^0 mesons, which are created by the interaction of accelerated hadrons with nuclei in the interstellar medium (Horns et al. 2006, 2007). In both cases, asymmetric crushing of the pulsar wind by the reverse shock of the expanding supernova remnant, in cases where the remnant has expanded into an asymmetric density distribution in the ambient medium, is then responsible for the offset between the pulsar and the peak of the VHE emission (de Jager & Djannati-Ataï 2008). A high pulsar proper motion may also play a role in the offset. The VHE emission could be a key into the earlier energetic history of these young pulsars as well as completing a broadband (radio to TeV γ-rays) picture of the shocked pulsar wind, whose emission would be dominated by synchrotron-emitting electrons below $\sim$1 GeV and inverse Compton emission from the scattering of these same particles above this energy.

In this Letter, we present the discovery and subsequent timing of the "Vela-like" pulsar (i.e., pulsars having characteristic age $\tau_c = 10$–30 kyr and spin-down luminosity $\dot{E} \sim 10^{36}$ ergs s^{-1}; e.g., Kramer et al. 2003) PSR J1856+0245 in the Arecibo PALFA survey of the Galactic plane. This young, energetic pulsar is positionally coincident with, and energetically capable of creating, the VHE emission observed from the hitherto unidentified TeV source HESS J1857+026 (Aharonian et al. 2008b). This association suggests that some of the other currently unidentified, extended HESS sources

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[18] See http://www.mpi-hd.mpg.de/hfm/HESS/public/HESS_catalog.htm for a catalog of HESS-detected sources.

[19] Note however that this situation does not appear to hold in the case of the youngest pulsars, e.g., the Crab, where there is no observed offset and the TeV emission is consistent with a point source. This possibly demonstrates the evolution of TeV PWNe with pulsar age.

TABLE 1

HESS VHE γ-Ray Sources Possibly Associated with PWNe

HESS Source	Size[a] (arcmin)	Pulsar/PWN	Offset (arcmin)	$P_{\rm spin}$ (ms)	τ_c (kyr)	$\dot{E}$ ($\times 10^{36}$ ergs s^{-1})	d[b] (kpc)	$L_\gamma/\dot{E}$ (1–10 TeV) (%)	Assoc. Ref.
J0534+220	...	B0531+21	...	33	1	460	2	0.009	1
J0835−455	26	B0833−45	18	89	11	6.9	0.3	0.008	2
J0852−463	60	J0855−4644	43	65	141	1.1	*2*	3	3
J1303−631	10	J1301−6305	11	185	11	1.7	*7*	5	4
J1418−609[c]	4	G313.3+0.1	8	...	...	...	...	...	5
J1420−607	4	J1420−6048	3	68	13	10	*6*	0.4	5
J1514−591	6	B1509−58	2	151	16	18	*4*	0.2	6
J1616−508	8	J1617−5055	10	69	8	16	*7*	0.6	7
J1640−465	3	G338.3−0.0	...	...	...	...	...	...	8
J1702−420	18	J1702−4128	35	182	55	0.34	*5*	5	9
J1718−385	9	J1718−3825	8	75	90	1.3	*4*	0.4	10
J1747−281	...	G0.9+0.1	...	...	...	...	...	...	11
J1804−216	12	B1800−21	10	134	16	2.2	*4*	2	12
J1809−193	32	J1809−1917	12	83	51	1.8	*4*	1	13
J1813−178	2	G12.8−0.0	...	...	...	...	...	...	14
J1825−137	10	B1823−13	11	101	21	2.8	*4*	1	15
J1833−105	...	J1833−1034	...	62	5	34	*3*	0.008	16
J1837−069	7	J1838−0655	6	70	23	5.5	7	1	17
J1846−029	...	J1846−0258	...	326	1	8.1	6	0.1	16
J1857+026	7	J1856+0245	8	81	21	4.6	*9*	3	18
J1912+101	16	J1913+1011	9	36	170	2.9	*5*	0.6	19

[a] This is the approximate source radius, taken from http://www.mpi-hd.mpg.de/hfm/HESS/public/HESS_catalog.htm when available. Some sources are consistent with being pointlike and thus no size is given.

[b] Distances in italics are obtained from the DM and the Cordes & Lazio (2002) model.

[c] No known radio pulsar, although possible X-ray pulsations with a period of 108 ms were reported by Ng et al. (2005).

References.—These are possible associations found in the literature. They are not all equally well established. (1) Aharonian et al. 2006c; (2) Aharonian et al. 2006b; (3) Aharonian et al. 2007b; (4) there are difficulties with the association of this HESS source with PSR J1301−6305 (see Mukherjee & Halpern 2005); (5) Aharonian et al. 2006a; (6) Aharonian et al. 2005c; (7) Landi et al. 2007; (8) Funk et al. 2007a; (9) Aharonian et al. 2006d; (10) Aharonian et al. 2007a; (11) Aharonian et al. 2005b; (12) Aharonian et al. 2006d (although the situation is unclear; see Kargaltsev et al. 2007); (13) Kargaltsev & Pavlov 2007; (14) Brogan et al. 2005, Helfand et al. 2007, Funk et al. 2007b; (15) Aharonian et al. 2005d; (16) Djannati-Ataï et al. 2007; (17) Gotthelf & Halpern 2008; (18) this paper; (19) Aharonian et al. 2008a.

in the Galactic plane may also be related to faint radio pulsars, rather than some new source class. An archival *ASCA* image of the area around PSR J1856+0245 and HESS J1857+026 shows a possible X-ray counterpart, cataloged as AX J185651+0245 by Sugizaki et al. (2001) at the pulsar position; this is possibly a synchrotron counterpart to the TeV PWN.[20]

2. OBSERVATIONS AND ANALYSIS

PSR J1856+0245 was discovered in the Arecibo PALFA survey for pulsars and radio transients (Cordes et al. 2006; see also Hessels 2007). PALFA is using the 1.4 GHz Arecibo L-band Feed Array (ALFA) seven-beam receiver to survey the Galactic plane at longitudes of $32° < l < 77°$ and $168° < l < 214°$, out to latitudes $|b| \leq 5°$. The relatively high observing frequency and unequaled raw sensitivity of the Arecibo telescope make the PALFA survey sensitive to distant, faint, and scattered pulsars that were missed in previous surveys. The larger goals, design, and observational setup of the PALFA survey are presented in detail by Cordes et al. (2006).

We found PSR J1856+0245 in a 268 s survey observation made on 2006 April 16. The pulsar was identified at a signal-to-noise ratio of 35 within a few minutes of the discovery observation itself through a "real time" processing pipeline, operating on data with reduced time and spectral resolution, which is automatically run on the survey data as they are being collected (Cordes et al. 2006). PSR J1856+0245 has a spin period of 81 ms and a large dispersion measure (DM), 622 cm^{-3} pc. We estimate that the flux density at 1400 MHz is $S_{1400} = 0.55 \pm 0.15$ mJy. We also note that PSR J1856+0245 shows a significant scattering tail at 1170 MHz ($\tau_{\rm sc} = 10 \pm 4$ ms at this frequency, where $\tau_{\rm sc}$ is the time constant of a one-sided exponential fitted to the pulse profile) and would be difficult to detect below ~800 MHz because the scattering timescale would be greater than the pulse period.

Immediately following the discovery of PSR J1856+0245, we began regular timing observations with Arecibo and the Jodrell Bank Observatory's 76 m Lovell Telescope in order to derive a precise rotational and astrometric ephemeris. Between the two telescopes, timing observations were made on 148 separate days between 2006 April 24 and 2008 April 18. At Arecibo, observations were made using both the center pixel of the ALFA receiver at 1440 MHz (identical setup to the standard PALFA survey mode) and the L-Wide receiver with multiple Wide-band Arecibo Pulsar Processor (WAPP) correlators centered at 1170, 1370, 1470, and 1570 MHz, each with 256 lags over 100 MHz of bandwidth, sampled every 256 μs. The typical integration time was 3 minutes. The Jodrell Bank observations were made at 1402/1418 MHz with a $2 \times 64 \times 1$ MHz incoherent filterbank system and 202 μs sampling time. The typical integration time was 20 minutes. The resulting phase-connected timing solution for PSR J1856+0245 is presented in Table 2 and combines data from both Arecibo and Jodrell Bank. This solution shows that PSR J1856+0245 is a Vela-like pulsar with a characteristic age of 21 kyr and a spin-down luminosity of $\dot{E} = 4.6 \times 10^{36}$ ergs s^{-1}. The solution was obtained using the TEMPO pulsar timing package.[21] The times of arrival (TOAs) can

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[20] Furthermore, in a recent reanalysis of EGRET γ-ray data, Casandjian & Grenier (2008) identified the source EGR J1856+0235, which is analogous to 3EG J1856+0114 in the third EGRET catalog. PSR J1856+0245 is well within the 95% confidence region of EGR J1856+0235, suggesting the pulsar and/or its PWN are also visible in the MeV–GeV range. We will investigate this further in a follow-up paper.

[21] See http://www.atnf.csiro.au/research/pulsar/tempo.

TABLE 2

Measured and Derived Parameters for PSR J1856+0245

Parameter	Value
Observation and Data Reduction Parameters	
Period epoch (MJD)	54167
Start time (MJD, Arecibo/Jodrell)	53849/53877
End time (MJD, Arecibo/Jodrell)	54570/54541
Number of TOAs (Arecibo/Jodrell)	78/134
TOA rms (ms)	1.8
Timing Parameters	
Right ascension[a] α (J2000.0)	$18^h56^m50.80^s \pm 0.02^s \pm 1.20^s$
Declination[a] δ (J2000.0)	$+02°45'50.2'' \pm 0.4'' \pm 8.0''$
Galactic longitude l	36.008°
Galactic latitude b	+0.058°
Pulse period P (s)	0.080902591336(5)
Period derivative $\dot{P}$	$6.2179(2) \times 10^{-14}$
Period second derivative[b] $\ddot{P}$ (s^{-1})	$-2.2(1) \times 10^{-24}$
Dispersion measure DM[c] (cm^{-3} pc)	622(2)
Derived Parameters	
Distance d (kpc)	~9
Spin-down luminosity $\dot{E}$ (ergs s^{-1})	4.6×10^{36}
Surface dipole magnetic field B (G)	2.3×10^{12}
Characteristic age τ_c (kyr)	21

Note.—Unless otherwise indicated, figures in parentheses are the 1 σ uncertainty on the least-significant digits quoted, from TEMPO.

[a] Includes the statistical error from TEMPO plus the much larger systematic error due to timing noise.

[b] Value is contaminated by timing noise.

[c] Uncertainty includes contaminating effects due to scattering.

be phase-connected by fitting only for position, DM, spin period P, period derivative $\dot{P}$, and period second derivative $\ddot{P}$, although further higher order period derivatives are required to remove all trends in the TOAs (i.e., to "whiten" the residuals). These higher order period derivatives, including $\ddot{P}$, are nondeterminisitic and are likely the result of timing noise, which is common in young pulsars. Timing noise affects the measured position of PSR J1856+0245 at a level exceeding the formal TEMPO uncertainties by an order of magnitude. Separately fitting the TOAs from the first and second years of timing gives positions which differ by ~9″. We take this as a rough measure of the true uncertainty on the timing-derived position of PSR J1856+0245.

The identification of PSR J1856+0245 as a young, energetic pulsar raises the likelihood that it powers a radio and/or X-ray PWN (for a review, see Kaspi et al. 2006). Accordingly, we have checked source catalogs and archival, multiwavelength data for other sources at the radio timing position of the pulsar. These searches revealed that PSR J1856+0245 is spatially coincident with the VHE γ-ray source HESS J1857+026 and the faint X-ray source AX J185651+0245. We discuss these possible associations in § 3.

3. DISCUSSION

PSR J1856+0245 is spatially coincident with the unidentified VHE γ-ray source HESS J1857+026 discovered by Aharonian et al. (2008b; see Fig. 1). Here we show that PSR J1856+0245 is energetically capable of powering HESS J1857+026 and that this association has similar characteristics to the other pulsar/VHE associations in the literature (Table 1).

The estimated distance to PSR J1856+0245, based on its DM and the NE2001 electron density model of the Galaxy (Cordes & Lazio 2002), is ~9 kpc. The uncertainty on this distance is not well defined but in some cases the model can be off by as much as a factor of ~2–3. Adopting DM distance 9 kpc gives a large spin-down flux $\dot{E}/d^2 = 5.7/d_9^2 \times 10^{34}$ ergs s^{-1} kpc^{-2}, where d_9 is the true distance scaled to 9 kpc. Carrigan et al. (2007) find that statistically 70% of pulsars with $\dot{E}/d^2 \gtrsim 10^{35}$ ergs s^{-1} kpc^{-2} are visible as VHE γ-ray sources. PSR J1856+0245 is very close to this limit and may exceed it if its distance is overestimated. Hence, based on its energetics alone, it is likely to be visible as a VHE γ-ray source. HESS J1857+026 has a photon index $\Gamma = 2.2$ and 1–10 TeV flux $F_{\rm VHE} = 1.5 \times 10^{-11}$ ergs cm^{-2} s^{-1} (about 15% of the Crab's flux in this energy range); these spectral parameters are similar to those measured for the other HESS sources identified with PWNe. Given the spin-down luminosity of PSR J1856+0245, this suggests an efficiency $\epsilon_\gamma = L_\gamma/\dot{E} = 3.1d_9^2$ % (1–10 TeV), comparable to what is seen in other proposed associations (Table 1).

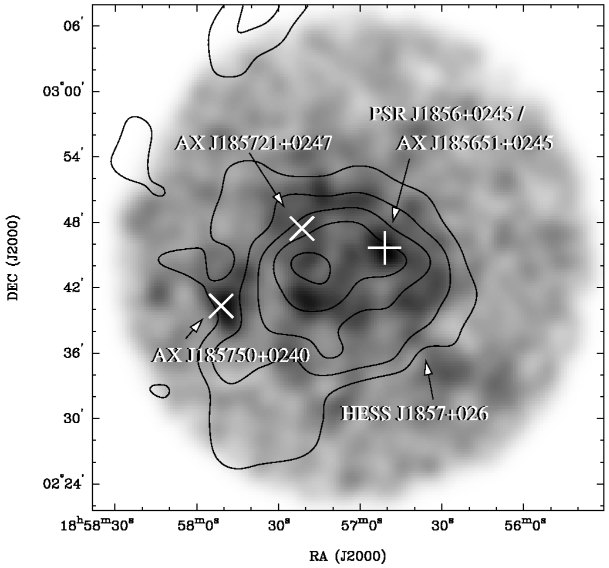

Fig. 1.—*ASCA* GIS image (2–10 keV) of the region surrounding PSR J1856+0245. This image has not been background subtracted or corrected for vignetting. The gray scale shows the GIS image smoothed with a 2′ (FWHM) Gaussian and scaled to bring out possible faint extended structure. The contours show significance levels of HESS J1857+026 from 5 to 9 σ, in steps of 1 σ (from Aharonian et al. 2008b). The plus marks PSR J1856+0245 and AX J185651+0245 and is much larger than the uncertainty on the pulsar's position. Two other nearby sources detected by Sugizaki et al. (2001), AX J185721+0247 and AX J185750+0240, are also marked. It is possible that AX J185721+0247 shows no excess in this image because it is faint and soft.

PSR J1856+0245 is offset from the centroid of HESS J1857+026, $\alpha = 18^h57^m11^s$, $\delta = +02°40'00''$ (J2000.0; there is a 3′ statistical uncertainty on this position), by 8′ (Fig. 1). As discussed in § 1, this is most likely explained by asymmetric confinement of the pulsar wind. This interpretation is supported by PSR J1856+0245's offset location on the side of HESS J1857+026 that appears somewhat compressed (i.e., there is a steep gradient in the γ-rays) compared with the rest of the nebula. If, however, the offset of the VHE emission is due primarily to the proper motion of PSR J1856+0245, then the direction and rough magnitude of this motion are predictable. Based on its characteristic age and offset from the centroid of HESS J1857+026, PSR J1856+0245's proper motion should be roughly 23 mas yr^{-1} (transverse velocity $v_t = 970d_9$ km s^{-1}), to the northwest, assuming that the centroid of HESS J1857+026 marks the birthplace of the pulsar. The velocity is very large, but not unprecedented for a pulsar (Chatterjee et al. 2005). Of course, the velocity will be smaller if the distance to the source is overestimated, or if the offset is at least partially due to an asymmetrically confined pulsar wind. Detecting this proper motion via timing or interferometry would elucidate this further and may be possible in the coming years, although timing noise and the low flux of the pulsar will make this difficult.

PSR J1856+0245 and HESS J1857+026 are also coincident with the faint *ASCA* X-ray source AX J185651+0245 reported by Sugizaki et al. (2001; see Fig. 1). AX J185651+0245 was found $3'$ off axis in observations from 1998 April 6 (sequence number 56003000). It was detected only in the hard band (2–10 keV) of the Gas Imaging Spectrometers (GISs), with a count rate of 2.6 ks^{-1} GIS^{-1} and a significance of 4.3 σ. The exposure was ~13 ks for each of GIS2 and GIS3. PSR J1856+0245 and AX J185651+0245 (J2000.0 position: $\alpha = 18^{\rm h}56^{\rm m}50^{\rm s}$, $\delta = +02°46'$) are spatially coincident to within the $1'$ positional uncertainty of sources in the Sugizaki et al. (2001) catalog. Although the signal-to-noise ratio of the detection of AX J185651+0245 is modest, its exact spatial coincidence with a young pulsar of relatively high spin-down flux argues that this source is real. Most of the previously established associations of HESS sources with young pulsars also have known X-ray synchrotron PWNe. AX J185651+0245 could be an X-ray PWN created by PSR J1856+0245. Using CXCPIMMS,[22] with an assumed absorbed power law spectrum with column density $N_{\rm H} = 1 \times 10^{22}$ cm^{-2} (roughly the total Galactic contribution in this direction) and photon index $\Gamma = 2$ (typical for X-ray PWNe), we find that AX J185651+0245 has an unabsorbed flux (2–10 keV) of 1.6×10^{-13} ergs s^{-1} cm^{-2}. This corresponds to an efficiency for the conversion of spin-down energy into X-rays $\epsilon_{\rm X} = L_{\rm X}/\dot{E} = 0.03 d_9^2$ % (2–10 keV) that falls into the observed range for Vela-like pulsars (Possenti et al. 2002). There are two additional nearby sources detected by Sugizaki et al. (2001): AX J185721+0247 and AX J185750+0240. It is possible that these are part of some extended X-ray emission related with HESS J1857+026, although deeper X-ray observations are needed to investigate this (see below).

There are four short *Swift* observations of the region containing PSR J1856+0245, including two observations specifically targeting AX J185651+0245. The deepest of these, from 2007 March 13 (observation ID 36183002), is a 4.1 ks on-axis exposure with the *Swift* X-Ray Telescope (XRT). This observation does not show any significant emission at the pulsar position; within a circular extraction region of radius $1'$ around the pulsar, the background subtracted number of counts is $1.1^{+4.0}_{-2.8}$. Using the aforementioned count rate of AX J185651+0245, along with the same assumed spectrum, the predicted 0.2–10 keV count rate for XRT from CXCPIMMS is ~2 counts ks^{-1}. Thus, in 4.1 ks, there should have been ~8 counts, consistent with the 2 σ upper limit derived from the data. Thus, if AX J185651+0245 is predominantly a point source, it was only at the limit of detectability in this observation. If it is predominantly an extended nebula, then it would not have been detectable in such a short exposure. Clearly, future, deeper observations, like those that recently discovered a likely X-ray PWN associated with HESS J1718−385/PSR J1718−3825 (Hinton et al. 2007), will be needed to determine the nature of this candidate X-ray PWN. We have been granted a ~60 ks *XMM-Newton* observation of PSR J1856+0245 and will present an analysis of those data in a follow-up paper.

At least half of the known HESS/pulsar associations are accompanied by radio emission classified as a PWN, a notable exception being HESS J1825−137/PSR B1823−13. Likewise, some of the extended HESS sources, e.g., HESS J0835−455, HESS J1813−178, and HESS J1640−465, are known to be accompanied by a supernova remnant (SNR). We have checked available radio imaging data for signs of a PWN or SNR. There is some faint, extended emission in the vicinity of PSR J1856+0245 visible in 1.4 GHz VLA Galactic Plane Survey data (VGPS; Stil et al. 2006), although nothing that is clearly indicative of a PWN or SNR. The surface brightness limit from VGPS is $\sim 1.8 \times 10^5$ Jy sr^{-1} at 1.4 GHz. It is certainly not uncommon for Vela-like pulsars to have faint or no known radio nebula (e.g., PSR B1823−13; Braun et al. 1989; Gaensler et al. 2003). Roughly a third of the cataloged Galactic SNRs (Green 2004) are fainter than the surface brightness limit achieved by the VGPS. Deep, dedicated radio imaging observations of PSR J1856+0245 are necessary to investigate this further. Higher resolution 1.4 GHz data from the MAGPIS survey (Helfand et al. 2006; in the vicinity of PSR J1856+0245, this survey has a sensitivity of 0.2 mJy beam^{-1} at an angular resolution of $6''$) reveal no point source which can be definitively associated with PSR J1856+0245, as expected given the flux density and positional uncertainty of the pulsar.

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[22] Available at http://cxc.harvard.edu/toolkit/pimms.jsp.

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