Todo list

OBSERVATIONS OF PWNE WITH THE FERMI GAMMA-RAY SPACE TELESCOPE

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List of Acronyms

1FHL the first *Fermi* hard-source list. 126

2CG the second COS-B catalog. 9

2FGL the second *Fermi* catalog. 22, 38, 122, 127

2PC the second *Fermi* pulsar catalog. 23, 124, 125

3EG the Third EGRET Catalog. 11

ACD Anti-Coincidence Detector. vii, 12

arcsec second of arc. 32

BPL broken-power law. 40

CGRO the Compton Gamma Ray Observatory. 10

CGS the Centimetre-Gram-Second System of Units. 40, 41

ECPL exponentially-cutoff power law. 40, 41

EGRET the Energetic Gamma Ray Experiment Telescope. xii, 9–11

ESA the European Space Agency. 9

FWHM full width at half maximum. 8

GBM Gamma-ray Burst Monitor. vii, 12

IACT Imaging air Cherenkov detector. 48, 119, 122, 126

IC inverse Compoton. 6, 19, 20, 31, 32, 35, 126

LAT the Large Area Telescope. iv, v, vii, viii, 12, 22, 23, 122, 123, 125–128, 132

MIT the Massachusetts Institute of Technology. 6, 13

MSC massive star cluster. 125

MSP millisecond pulsar. 27

NASA the National Aeronautics and Space Administration. 9, 10

NRL the Naval Research Laboratory. 13

NS neutron star. 13, 25, 26, 30

OSO-3 the Third Orbiting Solar Observatory. xii, 8, 9, 22

PL power law. 40, 41

PSF point spread function. 126

PWN pulsar wind nebula. iv, v, xiii, 1, 6, 14, 25, 29, 31–35, 122, 123, 125–129, 132

SA solid angle. 42, 43

SAS-2 the second Small Astronomy Satellite. 9, 10

SNR supernova remnant. 29, 32, 41

UNID unidentified source. 125, 126

VHE very high energy. ix, xi, 122–130, 134

Chapter 8

Search for PWNe associated with TeV Pulsars

This chapter is based the first part of the the paper "Constraints on the Galactic Population of TeV Pulsar Wind Nebulae using Fermi Large Area Telescope Observations" by Acero et al which is currently in prep.

In Chapter 6, we searched for spatially-extended sources in the 2FGL catalog. This search showed that the spatial analysis of *Fermi* sources is important in identifying γ-ray emitting pulsar wind nebulae (PWNe). In that work, we analyzed the γ-ray emitting PWNs HESS J1825−137 and MSH 15−52 which had previously been detected in the second *Fermi* catalog (2FGL). In addition, this analysis discovered that there were three additional spatially-extended *Fermi* sources coincident with PWNs candidates (HESS J1616−508, HESS J1632−478, HESS J1837−069).

In Chapter 7, we then searched for γ-ray emitting PWNs by looking in the off-peak emission of the Large Area Telescope (LAT)-detected pulsars. In that analysis, we detected four γ-ray emitting PWNs (Vela−X, the Crab Nebula, MSH 15−52, and 3C 58).

In this chapter, we continue our search for γ-ray emitting PWNs by searching for PWNs which had previously been detected at very high energy (VHE) energies by Imaging air Cherenkov detectors (IACTs). We note that the work presented here is a very condensed version of the results presented in the accompanying work (Acero et al. in prep.). We refer to that publication for a more detailed discussion of the analysis.

8.1 Introduction

We took all sources detected at VHE energies and potentially associated with PWNs and performed a search at GeV energies for γ-ray emission. As was seen in previous chapters, many PWNs have been detected both at GeV and VHE energies. Therefore, we suspect that by searching LAT data in the regiongs of VHE PWNs might yield the discovery of new LAT-detecting PWN.

In addition, there are several PWN which have been detected at VHE energies which do not have an associated γ-ray pulsar (such as HESS J1825−137 and HESS J1837−069). We therefore suspect that this search strategy may discovery new PWN which were not previously discovered either in the off-peak search discussed in Chapter 7 or in other dedicated analyses.

8.2 List of VHE PWN Candidates

Table 8.1. List of analyzed VHE sources

Name	Class	l (deg.)	b (deg.)	Pulsar	2PC	Reference
VER J0006+727	PWN	119.58	10.20	PSR J0007+7303	Y	McArthur (2011)
MGRO J0631+105	PWN	201.30	0.51	PSR J0631+1036	Y	Abdo et al. (2009c)
MGRO J0632+17	PWN	195.34	3.78	PSR J0633+1746	Y	Abdo et al. (2009c)
HESS J1018−589	UNID	284.23	−1.72	PSR J1016−5857	Y	H. E. S. S. Collaboration et al. (2012)
HESS J1023−575	MSC	284.22	−0.40	PSR J1023−5746	Y	H.E.S.S. Collaboration et al. (2011e)
HESS J1026−582	PWN	284.80	−0.52	PSR J1028−5819	Y	H.E.S.S. Collaboration et al. (2011e)
HESS J1119−614	PWN	292.10	−0.49	PSR J1119−6127	Y	Presentation[a]
HESS J1303−631	PWN	304.24	−0.36	PSR J1301−6305	N	Aharonian et al. (2005b)
HESS J1356−645	PWN	309.81	−2.49	PSR J1357−6429	Y	H.E.S.S. Collaboration et al. (2011d)
HESS J1418−609	PWN	313.25	0.15	PSR J1418−6058	Y	Aharonian et al. (2006b)
HESS J1420−607	PWN	313.56	0.27	PSR J1420−6048	Y	Aharonian et al. (2006b)
HESS J1427−608	UNID	314.41	−0.14	···	N	Aharonian et al. (2008c)
HESS J1458−608	PWN	317.75	−1.70	PSR J1459−6053	Y	de los Reyes et al. (2012)
HESS J1503−582	UNID	319.62	0.29	···	N	Renaud et al. (2008)
HESS J1507−622	UNID	317.95	−3.49	···	N	H.E.S.S. Collaboration et al. (2011c)
HESS J1514−591	PWN	320.33	−1.19	PSR J1513−5908	Y	Aharonian et al. (2005a)
HESS J1554−550	PWN	327.16	−1.07	···	N	Acero et al. (2012)
HESS J1616−508	PWN	332.39	−0.14	PSR J1617−5055	N	Aharonian et al. (2006e)
HESS J1626−490	UNID	334.77	0.05	···	N	Aharonian et al. (2008c)
HESS J1632−478	PWN	336.38	0.19	···	N	Aharonian et al. (2006e)
HESS J1634−472	UNID	337.11	0.22	···	N	Aharonian et al. (2006e)
HESS J1640−465	PWN	338.32	−0.02	···	N	Aharonian et al. (2006e)
HESS J1702−420	UNID	344.30	−0.18	PSR J1702−4128	Y	Aharonian et al. (2006e)
HESS J1708−443	PWN	343.06	−2.38	PSR J1709−4429	Y	H.E.S.S. Collaboration et al. (2011b)
HESS J1718−385	PWN	348.83	−0.49	PSR J1718−3825	Y	Aharonian et al. (2007a)
HESS J1729−345	UNID	353.44	−0.13	···	N	H.E.S.S. Collaboration et al. (2011a)
HESS J1804−216	UNID	8.40	−0.03	PSR J1803−2149	Y	Aharonian et al. (2006e)
HESS J1809−193	PWN	11.18	−0.09	PSR J1809−1917	N	Aharonian et al. (2007a)
HESS J1813−178	PWN	12.81	−0.03	PSR J1813−1749	N	Aharonian et al. (2006e)
HESS J1818−154	PWN	15.41	0.17	PSR J1818−1541	N	Hofverberg (2011)
HESS J1825−137	PWN	17.71	−0.70	PSR J1826−1334	N	Aharonian et al. (2006c)
HESS J1831−098	PWN	21.85	−0.11	PSR J1831−0952	N	Sheidaei (2011)
HESS J1833−105	PWN	21.51	−0.88	PSR J1833−1034	Y	Djannati-Ataï et al. (2008)
HESS J1834−087	UNID	23.24	−0.31	···	N	Aharonian et al. (2006e)
HESS J1837−069	UNID	25.18	−0.12	PSR J1836−0655	N	Aharonian et al. (2006e)
HESS J1841−055	UNID	26.80	−0.20	PSR J1838−0537	Y	Aharonian et al. (2008c)
HESS J1843−033	UNID	29.30	0.51	···	N	Hoppe (2008)
MGRO J1844−035	UNID	28.91	−0.02	···	N	Abdo et al. (2009c)

Table 8.1 (cont'd)

Name	Class	l (deg.)	b (deg.)	Pulsar	2PC	Reference
HESS J1846−029	PWN	29.70	−0.24	PSR J1846−0258	N	Djannati-Ataï et al. (2008)
HESS J1848−018	UNID	31.00	−0.16	···	N	Chaves et al. (2008)
HESS J1849−000	PWN	32.64	0.53	PSR J1849−001	N	Terrier et al. (2008)
HESS J1857+026	UNID	35.96	−0.06	PSR J1856+0245	N	Aharonian et al. (2008c)
HESS J1858+020	UNID	35.58	−0.58	···	N	Aharonian et al. (2008c)
MGRO J1900+039	UNID	37.42	−0.11	···	N	Abdo et al. (2009c)
MGRO J1908+06	UNID	40.39	−0.79	PSR J1907+0602	Y	Aharonian et al. (2009)
HESS J1912+101	PWN	44.39	−0.07	PSR J1913+1011	N	Aharonian et al. (2008b)
VER J1930+188	PWN	54.10	0.26	PSR J1930+1852	N	Acciari et al. (2010)
MGRO J1958+2848	PWN	65.85	−0.23	PSR J1958+2846	Y	Abdo et al. (2009c)
VER J1959+208	PSR	59.20	−4.70	PSR J1959+2048	Y	Hall et al. (2003)
VER J2016+372	UNID	74.94	1.15	···	N	Aliu (2011)
MGRO J2019+37	PWN	75.00	0.39	PSR J2021+3651	Y	Abdo et al. (2007)
MGRO J2031+41A	UNID	79.53	0.64	···	N	Abdo et al. (2007)
MGRO J2031+41B	UNID	80.25	1.07	PSR J2032+4127	Y	Bartoli et al. (2012)
MGRO J2228+61	PWN	106.57	2.91	PSR J2229+6114	Y	Abdo et al. (2009c)

[a]This source was presented at the "Supernova Remnants and Pulsar Wind Nebulae in the Chandra Era", 2009. See `http://cxc.harvard.edu/cdo/snr09/pres/DjannatiAtai_Arache_v2.pdf`.

Note. — The VHE sources that we searched for using LAT observations. The classifications come from TeVCat and are PWN for pulsar wind nebula, unidentified source (UNID) for unidentified source, and MSC for massive star cluster. We include HESS J1023−575 because it is potentially a PWN. For sources with an associated pulsar, column 4 includes the pulsar's name. Column 5 describes if the pulsar has been detected by the LAT and included in the second *Fermi* pulsar catalog (2PC) (See Chapter 7).

We used TeVCat to define the our target list of VHE sources. TeVCat is a catalog of sources detected at VHE energies by IACTs.[1] We selected all sources from this catalog where the emission was classified as being due to a PWN. In addition, we included all UNID sources within 5° of the galactic plane since they could be due to a PWN. Finally, we included HESS J1023−575. Although this source is classified as a massive star cluster in the TeVCat, de Naurois & H.E.S.S. Collaboration (2013) suggested that the emission could be due to PWN. The list of all sources included in our analysis as well as their classification in TeVCat can be found in Table 8.1.

8.3 Analysis Method

In this search, our analysis method was very similar to the analysis in Chapter 7. We used the same hybrid `pointlike`/`gtlike` approach for studying the spatial and spectral character of each source and modeled the region using the same standard background models.

The major difference was that this analysis was performed only for $E > 10\,\mathrm{GeV}$. As can be seen in Chapter 7, for energies much lower than 10 GeV, source analysis becomes strongly influenced by Galactic-diffuse emission and systematic errors associated with incorrectly modeling the emission. On the other hand, the γ-ray emission from PWN is expected to be the rising component of an inverse Compoton (IC) peak which falls at VHE energies. Therefore, the emission observed by the LAT is expected to be hard and most significant at higher energies. Therefore, we expect that starting the analysis at 10 GeV will significantly reduce systematics associated with this analysis while preserving most of the space for discovery.

Because the analysis was performed only in this high energy range where the point spread function (PSF) of the LAT is much improved, we were able to use a smaller region of interest (a radius of 5° in `pointlike` and a square of size $7° \times 7°$ in `gtlike`).

Another differences is that we used an event class with less background contamination (Pass 7 Clean instead of Pass 7 Source) and modeled nearby background sources using the first *Fermi* hard-source list (1FHL) (Ackermann et al. in prep).

[1] TeVCat can be found at `http://tevcat.uchicago.edu`.

For our analysis, we assume the GeV emission to have a power-law spectral model and to have whatever was the publisehd spatial model observed at VHE energies. We define $\mathrm{TS}_{\mathrm{TeV}}$ as the likelihood-ratio test for the significance of the source assuming it to have the power-law spectral model and the published VHE spatial model. We claim a detection when $\mathrm{TS}_{\mathrm{TeV}} > 16$. Our significance test has only two degrees of freedom: the flux and spectral index. Therefore, following Wilk's Theorem (see Section 5.3.1), this corresponds to a 3.6σ detection threshold. When the source is significantly-detected, we quote the best-fit spectral parameters and otherwise we derive a upper limit on the flux of any potential emission.

We note that Acero et al. (in prep.) performs a more detailed morphological analysis which also fits the positions of the sources assuming their emissions to be point-like and spatially-extended. That work then uses $\mathrm{TS}_{\mathrm{ext}}$ (See Section 5.2.2) to test if the emission is spatially-extended and otherwise computes an upper limit on any potential spatial extension. The more detailed analysis in Acero et al. (in prep.) is needed to compare the spatial overlap between the GeV and VHE emission. But for brevity, we omit the details and simply use the results.

We note that many of these PWNs candidates are in regions with LAT-detected pulars. For these sources, Acero et al. (in prep.) presents the spectral and spatial results both with and without the LAT-detected pulsar in the background model. For the analysis, the spectrum of these soruces of thse background pulsars was taken from the 2FGL catalog. For simplicity, we present only the analysis with the pulsar included in the background model. This analysis presents our best-guess at the true spectrum of any PWN emission. But we caution that this method could be biased in either oversubtracting or undersubtracting the pulsar depending upon systematics in the fit of the pulsar.

There are three major sources of systematic uncertainty effect the spectrum of these sources. The first systematic is due to uncertainty in our modeling of the Galactic diffuse emission. We estiamte this uncertainty following the method of Section 6.2. The second systematic is due to uncertainty in the effective area. We estimated the systematic using the method described in Ackermann et al. (2012). The final systematic is due to our uncertainty in the true morphology of of the source. We used as our

Table 8.2. Spatial and spectral results for detected VHE sources

Name	ID	TS_{TeV}	$F_{10\,GeV}^{316\,GeV}$ (10^{-10}ph cm^{-2}s^{-1})	Γ
HESS J1018−589	O	25	$1.5 \pm 0.5 \pm 0.7$	$2.31 \pm 0.50 \pm 0.49$
HESS J1023−575	PWNc	52	$4.6 \pm 0.9 \pm 1.2$	$1.99 \pm 0.24 \pm 0.32$
HESS J1119−614	PWNc	16	$2.0 \pm 0.6 \pm 0.8$	$1.83 \pm 0.41 \pm 0.36$
HESS J1303−631	PWNc	37	$3.6 \pm 0.9 \pm 2.1$	$1.53 \pm 0.23 \pm 0.37$
HESS J1356−645	PWN	24	$1.1 \pm 0.4 \pm 0.5$	$0.94 \pm 0.40 \pm 0.40$
HESS J1420−607	PWNc	36	$3.4 \pm 0.9 \pm 1.1$	$1.81 \pm 0.29 \pm 0.31$
HESS J1507−622	O	21	$1.5 \pm 0.5 \pm 0.5$	$2.33 \pm 0.48 \pm 0.48$
HESS J1514−591	PWN	156	$6.2 \pm 0.9 \pm 1.3$	$1.72 \pm 0.16 \pm 0.17$
HESS J1616−508	PWNc	75	$9.3 \pm 1.4 \pm 2.3$	$2.18 \pm 0.19 \pm 0.20$
HESS J1632−478	PWNc	137	$11.8 \pm 1.5 \pm 5.3$	$1.82 \pm 0.14 \pm 0.19$
HESS J1634−472	O	33	$5.6 \pm 1.3 \pm 2.5$	$1.96 \pm 0.25 \pm 0.29$
HESS J1640−465	PWNc	47	$5.0 \pm 1.0 \pm 1.7$	$1.95 \pm 0.23 \pm 0.20$
HESS J1708−443	PSR	33	$5.5 \pm 1.3 \pm 3.5$	$2.13 \pm 0.31 \pm 0.33$
HESS J1804−216	O	124	$13.4 \pm 1.6 \pm 3.1$	$2.04 \pm 0.16 \pm 0.24$
HESS J1825−137	PWN	56	$5.6 \pm 1.2 \pm 9.0$	$1.32 \pm 0.20 \pm 0.39$
HESS J1834−087	O	27	$5.5 \pm 1.2 \pm 2.5$	$2.24 \pm 0.34 \pm 0.42$
HESS J1837−069	PWNc	73	$7.5 \pm 1.3 \pm 4.2$	$1.47 \pm 0.18 \pm 0.30$
HESS J1841−055	PWNc	64	$10.9 \pm 0.8 \pm 4.1$	$1.60 \pm 0.27 \pm 0.33$
HESS J1848−018	PWNc	19	$7.4 \pm 1.9 \pm 2.7$	$2.46 \pm 0.50 \pm 0.51$
HESS J1857+026	PWNc	53	$4.2 \pm 0.3 \pm 1.3$	$1.01 \pm 0.24 \pm 0.25$
VER J2016+372	O	31	$1.8 \pm 0.5 \pm 0.8$	$2.45 \pm 0.44 \pm 0.49$

Note. — The results of our analysis search using LAT data for VHE PWNs. Column 2 says the classfication of the LAT emission (See Section 8.4). Column 3 is TS_{TeV}, columns 4 is the flux, and 5 is the spectral index all computed assuming a power-law spectral model (See Section 8.3 for a discussion of systematic errors).

systematic error on this the difference in spectrum when the source is fit assuming the published VHE spatial model and when using the spatial model measured by the LAT.

8.4 Sources Detected

We detected 22 sources. For significantly-detected sources, we present the spatial and spectral results for these sources in Table 9.1. Flux upper limits for non-detected sources as well as spectral points in three independent energy bins are can be found in Acero et al. (in prep.).

We attempt to classify the GeV emission into four categories: "PWN" for sources where the GeV emission is clearly identified PWN, "PWNc" for sources where the GeV emission could potentially be due to a PWN, "PSR" for sources where the emission is mostl likely due to pulsed emission inside the pulsar's magnetosphere, and "O" (for other) when the true nature of emission is uncertaint.

W categorize a source as "PWN" or "PWNc" when the emission has a hard spectrum which connects spectrally to the VHE spectrum and when there is some muliwavelenth evidence that the GeV and VHE emission should be due to a pulsar-wind nebula. We put a source in the "PWN" when the VHE emission suggests more strongly that the emission is due to the pulsar wind nebula. We will discuss the muliwavelent evidence for each "PWN" source in Section 8.4.1. We include in Table 9.1 the source classifications.

Mention that Acero et al. (in prep.). has a better discussion of the sources

8.4.1 "PWN" and "PWNc" Sources

In total, we detect fourteen sources which we classify as "PWN" or "PWNc". Five of these PWN and PWN candidates are first reported in this analysis.

Of these fourteen sources, three are classified as "PWN". They are HESS J1356−645, MSH 15−52 (HESS J1514−591), and HESS J1825−137. HESS J1356−645 and MSH 15−52 are classified as "PWN" because of the correlation between the X-ray and VHE emission (H.E.S.S. Collaboration et al. 2011d; Aharonian et al. 2005a). HESS J1825−137 is classified as "PWN" because of the energy-dependent morphology observed at VHE energies (Aharonian et al. 2006c). We note that HESS J1356−645 was first presented as an PWN in this work. Once we add the Crab Nebula and Vela−X (not analyzed in this work) to this list, the total number of clearly-identified PWNs detected at GeV energies is five.

In addition, we detect 11 "PWNc"-type sources. Four of these sources are first reported in this work: HESS J1119−614, HESS J1303−631, HESS J1420−607, and HESS J1841−055. These sources are all powered by pulsars energetic enough to power the observed emission (PSR J1119−6127, PSR J1301−6305, PSR J1420−6048, PSR J1838−0537), and they all have a hard spectrum which connects to the spectra observed at VHE energies.

We caution that two of these sources have an associated LAT-detected pulsar and were therefore studied in Chapter 7.

We mention that PSR J1119−6127, PSR J1420−6048, and PSR J1838−0537 are all detected by the LAT and therefore were studied in Section **??**. In Section **??**, PSR J1119−6127 has TS = 61.3 and is classified as a "U"-type source because the spectrum is relativly soft (spectral index~ 2.2). But in the off-peak analysis, one can observe a faint hard component of the emission at high energy as well as a stronger component at low energy. In the off-peak analysis, we calculated TS = 13.8 in the energy range from 10 GeV to 316 GeV when computing an SED with a fixed spectral index of 2. So the off-peak analysis is fairly consistent with this work.

For PSR J1420−6048, . . . `http://www.slac.stanford.edu/~lande/pwnpipeline/v37/website/PSRJ1420-6048.html`

The off-peak analysis of PSR J1838−0537 detects a soft and significantly-cutoff spectrum which is `http://www.slac.stanford.edu/~lande/pwnpipeline/v37/website/PSRJ1838-0537.html` In the residual test-statistic map, there is significant emission towards the position of HESS J1841−055. The off-peak emission is sigificantly-extended. Tehrefore our analysis are most-likely compatable.

Mention that Acero et al. (in prep.) has a better discussion of the sources detected for the new PWN

The remaining seven sources have been previously published: HESS J1023−575 (Ackermann et al. 2011a), HESS J1640−465 (Slane et al. 2010), HESS J1616−508 (Lande et al. 2012), HESS J1632−478 (Lande et al. 2012), HESS J1837−069 (Lande et al. 2012), HESS J1848−018 (Tam et al. 2010), and HESS J1857+026 (Rousseau et al. 2012b).

Finally, note that we have add HESS J1848−018 to the list of "PWNc" sources even though the GeV emission has a soft spectrum because of the careful multiwavelenth considerations presented in Lemoine-Goumard et al. (2011).

8.4.2 "O" Sources

The third category is "O"...

8.4.3 "PSR" Sources

The final category is "PSR"...

Forward reference population study in .

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