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OBSERVATIONS OF PWNE WITH THE FERMI GAMMA-RAY
SPACE TELESCOPE

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF PHYSICS
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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DOCTOR OF PHILOSOPHY

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List of Acronyms

1FHL the first *Fermi* hard-source list. 127

2CG the second COS-B catalog. 9

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

2PC the second *Fermi* pulsar catalog. 23

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, 123, 126

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

LAT the Large Area Telescope. iv, v, vii, viii, 12, 22, 23, 122, 125, 126, 128, 130

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, 126, 128, 130

SA solid angle. 42, 43

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

SNR supernova remnant. 29, 32, 41

UNID unidentified source. 125

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.

TODO:

- Strip out sources not classified as PWN/PSR
- Remove the fit without the LAT PSR included in the background model.

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 this 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* soruces coincident with PWNs candidates (HESS J1616–508, HESS J1632–478, HESS J1837–069). In Chapter ??, we then searched for γ -ray emitting PWNs by looking in the off-peak emission of the Large Area Telescope (LAT)-detected pulsars. In this analysis, we detected four γ -ray emitting PWNs candidates (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 TeV 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

In this analysis, we took all sources detected at TeV energies and potentially associated with PWNs and performed a search at GeV energies for γ -ray emission. As was seen in previous sections, many sources such as the Crab Nebula and Vela–X had been observed at both GeV and TeV energies. In addition, there are several PWN which have been detected at TeV energies which do not have an associated γ -ray pulsar (such as HESS J1825–137 and HESS J1837–069). We therefore suspect that a thorough search of all TeV PWNs candidates might discover new γ -ray emitting PWNs not previously discovered either in the off-peak search discussed in Chapter ?? or in other dedicated analyses.

8.2 List of TeV PWN Candidates

Table 8.1. List of analyzed TeV sources

Name	Class	l (deg.)	b (deg.)	LAT PSR	Reference
VER J0006+727	PWN	119.58	10.20	PSR J0007+7303	?
MGRO J0631+105	PWN	201.30	0.51	PSR J0631+1036	?
MGRO J0632+17	PWN	195.34	3.78	PSR J0633+1746	?
HESS J1018-589	UNID	284.23	-1.72	PSR J1016-5857	?
HESS J1023-575	MSC	284.22	-0.40	PSR J1023-5746	?
HESS J1026-582	PWN	284.80	-0.52	PSR J1028-5819	?
HESS J1119-614	PWN	292.10	-0.49	PSR J1119-6127	Presentation ^a
HESS J1303-631	PWN	304.24	-0.36	...	?
HESS J1356-645	PWN	309.81	-2.49	PSR J1357-6429	?
HESS J1418-609	PWN	313.25	0.15	PSR J1418-6058	?
HESS J1420-607	PWN	313.56	0.27	PSR J1420-6048	?
HESS J1427-608	UNID	314.41	-0.14	...	?
HESS J1458-608	PWN	317.75	-1.70	PSR J1459-6053	?
HESS J1503-582	UNID	319.62	0.29	...	?
HESS J1507-622	UNID	317.95	-3.49	...	?
HESS J1514-591	PWN	320.33	-1.19	PSR J1513-5908	?
HESS J1554-550	PWN	327.16	-1.07	...	?
HESS J1616-508	PWN	332.39	-0.14	...	?
HESS J1626-490	UNID	334.77	0.05	...	?
HESS J1632-478	PWN	336.38	0.19	...	?
HESS J1634-472	UNID	337.11	0.22	...	?
HESS J1640-465	PWN	338.32	-0.02	...	?
HESS J1702-420	UNID	344.30	-0.18	PSR J1702-4128	?
HESS J1708-443	PWN	343.06	-2.38	PSR J1709-4429	?
HESS J1718-385	PWN	348.83	-0.49	PSR J1718-3825	?
HESS J1729-345	UNID	353.44	-0.13	...	?
HESS J1804-216	UNID	8.40	-0.03	PSR J1803-2149	?
HESS J1809-193	PWN	11.18	-0.09	...	?
HESS J1813-178	PWN	12.81	-0.03	...	?
HESS J1818-154	PWN	15.41	0.17	...	?
HESS J1825-137	PWN	17.71	-0.70	...	?
HESS J1831-098	PWN	21.85	-0.11	...	?
HESS J1833-105	PWN	21.51	-0.88	PSR J1833-1034	?
HESS J1834-087	UNID	23.24	-0.31	...	?
HESS J1837-069	UNID	25.18	-0.12	...	?
HESS J1841-055	UNID	26.80	-0.20	PSR J1838-0537	?
HESS J1843-033	UNID	29.30	0.51	...	?
MGRO J1844-035	UNID	28.91	-0.02	...	?

Table 8.1 (cont'd)

Name	Class	l (deg.)	b (deg.)	LAT PSR	Reference
HESS J1846–029	PWN	29.70	–0.24	...	?
HESS J1848–018	UNID	31.00	–0.16	...	?
HESS J1849–000	PWN	32.64	0.53	...	?
HESS J1857+026	UNID	35.96	–0.06	...	?
HESS J1858+020	UNID	35.58	–0.58	...	?
MGRO J1900+039	UNID	37.42	–0.11	...	?
MGRO J1908+06	UNID	40.39	–0.79	PSR J1907+0602	?
HESS J1912+101	PWN	44.39	–0.07	...	?
VER J1930+188	PWN	54.10	0.26	...	?
MGRO J1958+2848	PWN	65.85	–0.23	PSR J1958+2846	?
VER J1959+208	PSR	59.20	–4.70	PSR J1959+2048	?
VER J2016+372	UNID	74.94	1.15	...	?
MGRO J2019+37	PWN	75.00	0.39	PSR J2021+3651	?
MGRO J2031+41A	UNID	79.53	0.64	...	?
MGRO J2031+41B	UNID	80.25	1.07	PSR J2032+4127	?
MGRO J2228+61	PWN	106.57	2.91	PSR J2229+6114	?

^aThis 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 TeV 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 LAT-detected pulsar, column 4 includes the pulsar's name.

We used TeVCat to define the list of TeV sources to search for GeV PWNs. TeVCat is a catalog of sources detected at TeV energies by IACTs¹. We selected all sources from this catalog where the emission was classified as being due to a PWN. In addition, we included all sources with an UNID classification (unidentified emission) within 5° of the galactic plane, since they could potentially be due to a PWN. Finally, we included HESS J1023–575 which, although classified as a massive star cluster in the TeVCat, was suggested to be a PWN in de Naurois & H.E.S.S. Collaboration (2013). 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 ???. 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 $E > 10$ GeV. As can be seen in Chapter ??, 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 Compton (IC) peak which falls at TeV 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 $7^\circ \times 7^\circ$ in `gtlike`).

Another difference is that we used an event class with less background contamination (Pass 7 Clean instead of Pass 7 Source) and modeled nearby background sources

¹TeVCat can be found at <http://tevcat.uchicago.edu>.

using the first *Fermi* hard-source list (1FHL) Ackermann et al. (in prep).

For our analysis, we assume the GeV emission to have a power law spectral model and to have whatever was the best-fit spatial model observed at TeV energies. We define TS_{TeV} as the likelihood-ratio test for the significance of the source assuming it to have the power-law spectral model and TeV spatial model. We consider a source to be detected when $\text{TS}_{\text{TeV}} > 16$. 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 fits the positions of the sources assuming the emissions to be point-like and spatially-extended. The work uses the TS_{ext} test defined in Section 5.2.2 to test if the emission is spatially-extended and otherwise computes an upper limit on any potential spatial extension. This additional analysis is relevant for comparing the spatial overlap between the GeV and TeV emission. But for brevity, we omit the details and refer to that publication.

TODO, discuss issue about soruces with a nearby LAT-detcted pulsar. Which soruces have a LAT-dtected pulasr, what does Acero et al. (in prep.) do about this?

In addition Acero et al. (in prep.) performs a careful study of the systematics associated with this analysi.

WHAT SYSTEMATICS

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8.4 Sources Detected

We detect 22 sources which are statistically significant. We present the spatial and spectarl results for these sources in Table ??.

We classify these sources into four categories. The first category is “PWN” which is when there is

The second category is “PWNe”...

Table 8.2. Spatial and spectral results for detected TeV sources

Name	ID	TS _{TeV}	$F_{10\text{ GeV}}^{316\text{ GeV}}$ ($10^{-10}\text{ ph cm}^{-2}\text{ s}^{-1}$)	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 TeV PWNs. Column 2 says the classification of the LAT emission (See Section 8.4). Column 3 is TS_{TeV}, and columns 4 and 5 are the flux and spectral index computed assuming a power-law spectral model (See Section 8.3 for a discussion of systematic errors).

The third category is “PSR”...

The final category is “O”...

TODO, mention how modeling pulsar in background could be somewaht biased.

WHERE ARE RESULTS PRESENTED

. We don’t quote upper limits, for some reason....

- We detected 4 new PWNe candidates (HESS J1119–614, HESS J1303–631, HESS J1420–607, and HESS J1841–055) and 1 new PWN (HESS J1356–645)

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HESS J1023-575 HESS J1119-614 HESS J1303-631 HESS J1356-645 HESS J1420-607 HESS J1514-591 HESS J1616-508 HESS J1632-478 HESS J1640-465 HESS J1825-137 HESS J1837-069 (UNID) HESS J1841-055 (UNID) HESS J1848-018 (UNID) HESS J1857+026 (UNID)

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