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OBSERVATIONS OF PWNE WITH THE FERMI GAMMA-RAY
SPACE TELESCOPE

A DISSERTATION
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AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
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DOCTOR OF PHILOSOPHY

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List of Acronyms

1FHL the first *Fermi* hard-source list. 122

2CG the second COS-B catalog. 8

2FGL the second *Fermi* catalog. 21, 36, 118, 123

2PC the second *Fermi* pulsar catalog. 22, 120, 121

3EG the Third EGRET Catalog. 9

ACD Anti-Coincidence Detector. 11

arcsec second of arc. 31

BPL broken-power law. 38

CGRO the Compton Gamma Ray Observatory. 8

CGS the Centimetre-Gram-Second System of Units. 38, 39

ECPL exponentially-cutoff power law. 38, 39

EGRET the Energetic Gamma Ray Experiment Telescope. 8–10

ESA the European Space Agency. 8

FWHM full width at half maximum. 6

GBM Gamma-ray Burst Monitor. 11

IACT Imaging air Cherenkov detector. 46, 115, 118, 122

IC inverse Compton. 4, 18, 19, 30, 31, 34, 122

LAT the Large Area Telescope. iv, v, 11, 21, 22, 118, 119, 121–123, 125, 127

MIT the Massachusetts Institute of Technology. 6, 12

MSC massive star cluster. 121

MSP millisecond pulsar. 26

NASA the National Aeronautics and Space Administration. 7, 8

NRL the Naval Research Laboratory. 12

NS neutron star. 12, 24, 25, 28, 29

OSO-3 the Third Orbiting Solar Observatory. 6, 7, 20

PL power law. 38, 39

PSF point spread function. 122

PWN pulsar wind nebula. iv, v, 5, 13, 24, 28, 30–34, 118, 119, 121–125, 127

SA solid angle. 40, 41

SAS-2 the second Small Astronomy Satellite. 7, 8

SNR supernova remnant. 28, 30, 31, 39

UNID unidentified source. 121, 122

VHE very high energy. 118–125, 129

Chapter 9

Population Study of LATs-detected PWNe

This chapter is based the second 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 search for new spatially-extended *Fermi* sources and found that spatial extension was an important characteristic for detecting new pulsar wind nebulae (PWNe). In the process, we discovered three new γ -ray emitting PWNs. In Chapter 7, we then searched in the off-peak phase interval of the Large Area Telescope (LAT)-detected pulsars for new pulsar wind nebula and discovered 3C 58. Finally, in Chapter 8 we searched in the regions surrounding PWNs candidates detected at TeV energies for GeV-emitting PWNs 4 new PWNe candidates (HESS J1119–614, HESS J1303–631, HESS J1420–607, and HESS J1841–055) and 1 new PWN (HESS J1356–645)

In this chapter, we take the population of γ -ray emitting PWNs and PWNs candidates

9.1 Summary of the PWNe detected by the LATs

9.2 The Evolution of γ -ray Emitting PWNe with the Properties of their Pulsars

Table 9.1.

Source	$F_{1\text{ TeV}}^{30\text{ TeV}}$ ($10^{-12}\text{erg cm}^{-2}\text{s}^{-1}$)	$F_{1\text{ KeV}}^{10\text{ KeV}}$ ($10^{-12}\text{erg cm}^{-2}\text{s}^{-1}$)	PSR	\dot{E} (erg s^{-1})	τ (kyr)	Distance (kpc)
VERJ0006+727	...	...	PSRJ0007+7303	4.5e+35	13.9	1.4 ± 0.3
Crab	80 ± 16	21000 ± 4200	PSR J0534+2200	4.6e+38	1.2	2.0 ± 0.5
MGROJ0631+105	...	...	PSRJ0631+1036	1.7e+35	43.6	1.00 ± 0.20
MGROJ0632+17	...	...	PSRJ0633+1746	3.2e+34	342	$0.2^{+0.2}_{-0.1}$
Vela-X	79 ± 21	54 ± 11	PSRJ0835-4510	6.9e+36	11.3	0.29 ± 0.02
HESSJ1018-589	0.9 ± 0.4	...	PSRJ1016-5857	2.6e+36	21	3
HESSJ1023-575	4.8 ± 1.7	...	PSRJ1023-5746	1.1e+37	4.6	2.8
HESSJ1026-582	5.9 ± 4.4	...	PSRJ1028-5819	8.4e+35	90	2.3 ± 0.3
HESSJ1119-614	2.3 ± 1.2	...	PSRJ1119-6127	2.3e+36	1.6	8.4 ± 0.4
HESSJ1303-631	27 ± 1	0.16 ± 0.03	PSRJ1301-6305	1.7e+36	11	$6.7^{+1.1}_{-1.2}$
HESSJ1356-645	6.7 ± 3.7	0.06 ± 0.01	PSRJ1357-6429	3.1e+36	7.3	$2.5^{+0.5}_{-0.4}$
HESSJ1418-609	3.4 ± 1.8	3.1 ± 0.1	PSRJ1418-6058	4.9e+36	1	1.6 ± 0.7
HESSJ1420-607	15 ± 3	1.3 ± 0.3	PSRJ1420-6048	1.0e+37	13	5.6 ± 0.9
HESSJ1458-608	3.9 ± 2.4	...	PSRJ1459-6053	9.1e+35	64.7	4
HESSJ1514-591	20 ± 4	29 ± 6	PSRJ1513-5906	1.7e+37	1.56	4.2 ± 0.6
HESSJ1554-550	1.6 ± 0.5	3.1 ± 1.0	...	...	18	7.8 ± 1.3
HESSJ1616-508	21 ± 5	4.2 ± 0.8	PSRJ1617-5055	1.6e+37	8.13	6.8 ± 0.7
HESSJ1632-478	15 ± 5	0.43 ± 0.08	...	3.0e+36	20	3
HESSJ1640-465	5.5 ± 1.2	0.46 ± 0.09	...	4.0e+36	...	...
HESSJ1646-458B	5.0 ± 2.0	...	PSRJ1648-4611	2.1e+35	110	5.0 ± 0.7
HESSJ1702-420	44 ± 8	0.01 ± 0.00	PSRJ1702-4128	3.4e+35	55	4.8 ± 0.6
HESSJ1708-443	23 ± 7	...	PSRJ1709-4429	3.4e+36	17.5	2.3 ± 0.3
HESSJ1718-385	4.3 ± 1.6	0.14 ± 0.03	PSRJ1718-3825	1.3e+36	89.5	3.6 ± 0.4
HESSJ1804-216	12 ± 2	0.07 ± 0.01	PSRJ1803-2137	2.2e+36	16	$3.8^{+0.4}_{-0.5}$
HESSJ1809-193	19 ± 6	0.23 ± 0.05	PSRJ1809-1917	1.8e+36	51.3	3.5 ± 0.4
HESSJ1813-178	5.0 ± 0.6	...	PSRJ1813-1749	6.8e+37	5.4	4.7
HESSJ1818-154	1.3 ± 0.9	...	PSRJ1818-1541	2.3e+33	9	$7.8^{+1.6}_{-1.4}$
HESSJ1825-137	61 ± 14	0.44 ± 0.09	PSRJ1826-1334	2.8e+36	21	3.9 ± 0.4
HESSJ1831-098	5.1 ± 0.6	...	PSRJ1831-0952	1.1e+36	128	4.0 ± 0.4
HESSJ1833-105	2.4 ± 1.2	40 ± 0	PSRJ1833-1034	3.4e+37	4.85	4.7 ± 0.4
HESSJ1837-069	23 ± 9	0.64 ± 0.24	PSRJ1836-0655	5.5e+36	2.23	6.6 ± 0.9
HESSJ1841-055	23 ± 3	...	PSRJ1838-0537	5.9e+36	4.97	1.3
HESSJ1846-029	9.0 ± 1.5	29 ± 1	PSRJ1846-0258	8.1e+36	0.73	5.1
HESSJ1848-018	4.3 ± 1.0	...	...	...	...	6
HESSJ1849-000	2.1 ± 0.4	0.90 ± 0.20	PSRJ1849-001	9.8e+36	42.9	7
HESSJ1857+026	18 ± 3	...	PSRJ1856+0245	4.6e+36	20.6	9.0 ± 1.2
MGROJ1908+06	12 ± 5	...	PSRJ1907+0602	2.8e+36	19.5	3.2 ± 0.3
HESSJ1912+101	7.3 ± 3.7	...	PSRJ1913+1011	2.9e+36	169	$4.8^{+0.5}_{-0.7}$

Table 9.1 (cont'd)

Source	$F_{1\text{ TeV}}^{30\text{ TeV}}$ ($10^{-12}\text{erg cm}^{-2}\text{s}^{-1}$)	$F_{1\text{ KeV}}^{10\text{ KeV}}$ ($10^{-12}\text{erg cm}^{-2}\text{s}^{-1}$)	PSR	\dot{E} (erg s^{-1})	τ (kyr)	Distance (kpc)
VERJ1930+188	2.3 ± 1.3	5.2 ± 0.1	PSRJ1930+1852	$1.2\text{e}+37$	2.89	9^{+7}_{-2}
VERJ1959+208	...	...	PSRJ1959+2048	$1.6\text{e}+35$	...	2.5 ± 1.0
MGROJ2019+37	...	...	PSRJ2021+3651	$3.4\text{e}+36$	17.2	10^{+2}_{-4}
MGROJ2228+61	...	0.88 ± 0.02	PSRJ2229+6114	$2.2\text{e}+37$	10.5	0.80 ± 0.20

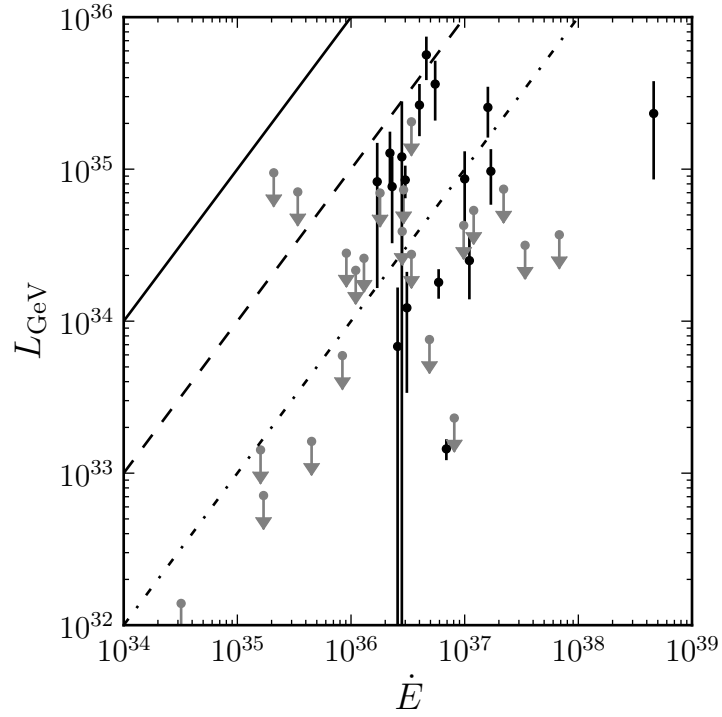


Figure 9.1 ...

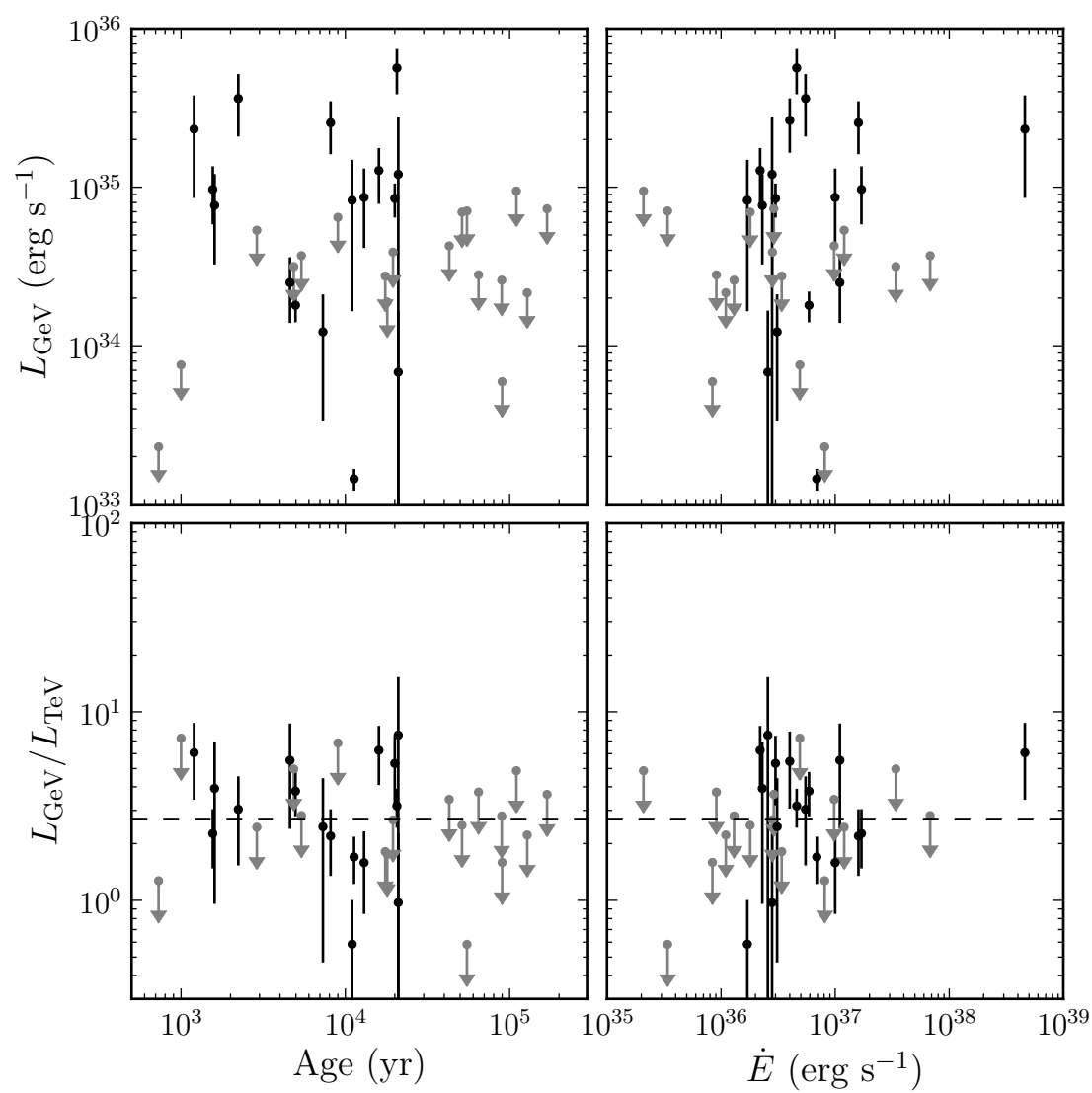


Figure 9.2 ...

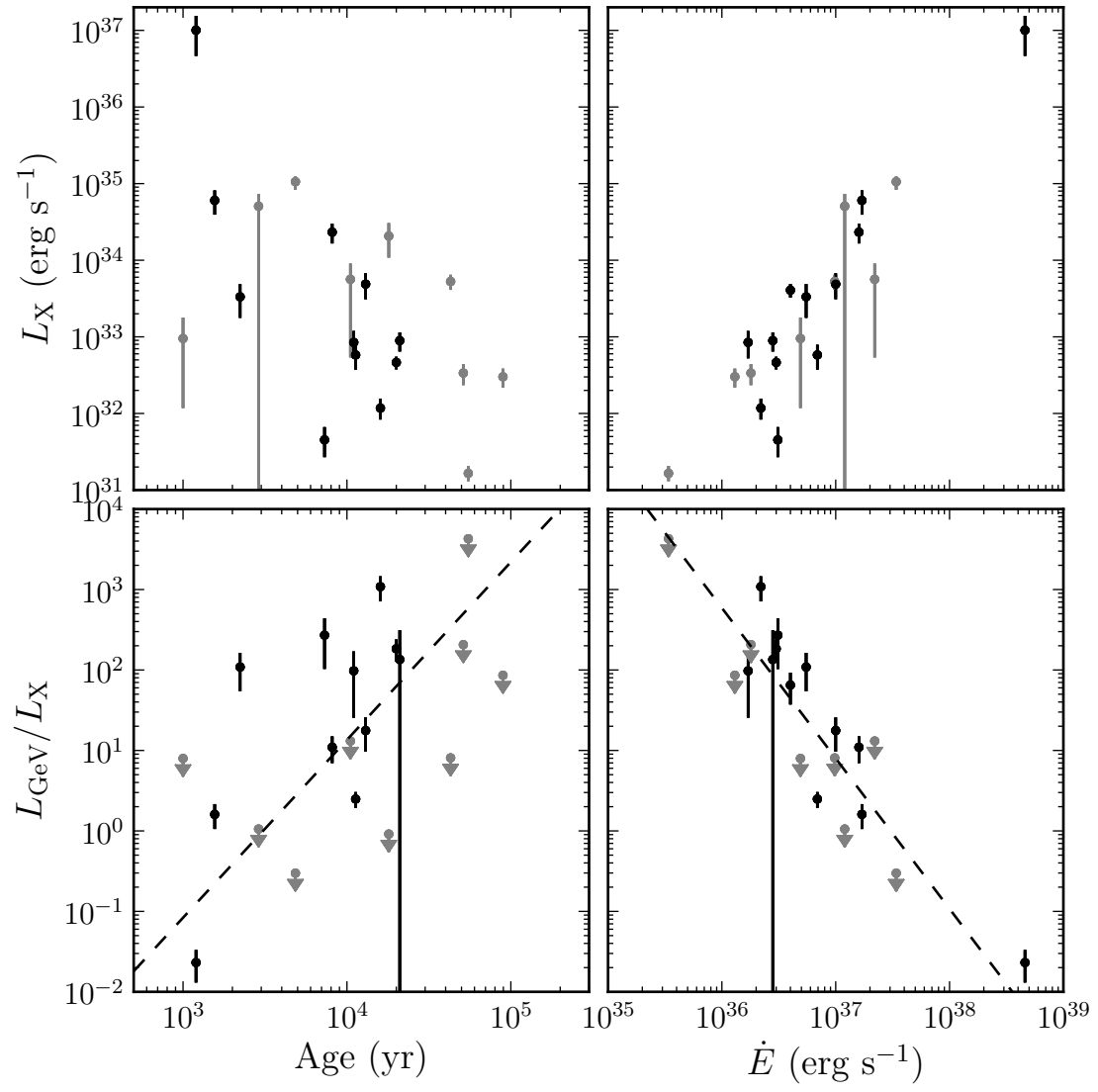


Figure 9.3 ...

Bibliography

- Abdo, A., Ackermann, M., Ajello, M., et al. 2010, *Astrophys.J.*, 722, 1303
- Abdo, A. A., Allen, B., Berley, D., et al. 2007, *ApJ*, 664, L91
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009a, *ApJ*, 706, L1
- . 2009b, *ApJS*, 183, 46
- Abdo, A. A., Allen, B. T., Aune, T., et al. 2009c, *ApJ*, 700, L127
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009d, *Astroparticle Physics*, 32, 193
- . 2010a, *ApJ*, 714, 927
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, *A&A*, 523, A46
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010c, *Science*, 328, 725
- . 2010d, *ApJS*, 188, 405
- . 2010e, *ApJ*, 708, 1254
- . 2010f, *ApJ*, 718, 348
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, *The Astrophysical Journal*, 713, 146
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, *Science*, 327, 1103
- . 2010b, *ApJ*, 712, 459

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010c, *A&A*, 512, A7
- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010d, *Physical Review Letters*, 104, 101101
- . 2010e, *ApJS*, 187, 460
- . 2011, *ApJ*, 734, 28
- Acciari, V. A., Aliu, E., Arlen, T., et al. 2009, *ApJ*, 698, L133
- . 2010, *ApJ*, 719, L69
- . 2011, *ApJ*, 738, 3
- Acerro, F., Ackermann, M., Ajello, M., & et al. in prep., *ApJ*
- Acerro, F., Djannati-Ataï, A., Förster, A., et al. 2012, *ArXiv e-prints*
- Ackermann, M., Ajello, M., Allafort, A., et al. in prep, *ApJ*
- . 2011, *ApJ*, 743, 171
- Ackermann, M., Ajello, M., Albert, A., et al. 2012, *ApJS*, 203, 4
- Aharonian, F., Akhperjanian, A. G., Aye, K.-M., et al. 2005a, *A&A*, 435, L17
- . 2005b, *A&A*, 439, 1013
- Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006a, *A&A*, 460, 743
- . 2006b, *A&A*, 456, 245
- . 2006c, *A&A*, 460, 365
- . 2006d, *A&A*, 448, L43
- . 2006e, *ApJ*, 636, 777
- . 2007a, *A&A*, 472, 489

—. 2007b, *ApJ*, 661, 236

—. 2007c, *A&A*, 464, 235

—. 2008a, *A&A*, 481, 401

Aharonian, F., Akhperjanian, A. G., Barres de Almeida, U., et al. 2008b, *A&A*, 484, 435

—. 2008c, *A&A*, 477, 353

Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, *A&A*, 499, 723

Aharonian, F. A., & Bogovalov, S. V. 2003, *New A*, 8, 85

Aharonian, F. A., Coppi, P. S., & Voelk, H. J. 1994, *ApJ*, 423, L5

Aharonian, F. A., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2007d, *A&A*, 469, L1

Ajello, M., Allafort, A., Baldini, L., et al. 2012, *ApJ*, 744, 80

Akaike, H. 1974, *IEEE Transactions on Automatic Control*, 19, 716

Albert, J., Aliu, E., Anderhub, H., et al. 2006, *Science*, 312, 1771

Aliu, E. 2011, in *International Cosmic Ray Conference*, Vol. 7, *International Cosmic Ray Conference*, 227

Arnold, J. R., Metzger, A. E., Anderson, E. C., & van Dilla, M. A. 1962, *J. Geophys. Res.*, 67, 4878

Arons, J. 1996, *Space Sci. Rev.*, 75, 235

Ashworth, William B., J. 1981, *Proceedings of the American Philosophical Society*, 125, pp. 52

Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, *ApJ*, 697, 1071

- Balbo, M., Saouter, P., Walter, R., et al. 2010, *A&A*, 520, A111
- Baltz, E. A., Berenji, B., Bertone, G., et al. 2008, *J. Cosmology Astropart. Phys.*, 7, 13
- Bamba, A., Ueno, M., Koyama, K., & Yamauchi, S. 2003, *The Astrophysical Journal*, 589, 253
- Bartoli, B., Bernardini, P., Bi, X. J., et al. 2012, *ApJ*, 745, L22
- Baum, W. A., Johnson, F. S., Oberly, J. J., et al. 1946, *Phys. Rev.*, 70, 781
- Bertsch, D. L., Brazier, K. T. S., Fichtel, C. E., et al. 1992, *Nature*, 357, 306
- Bignami, G. F., Boella, G., Burger, J. J., et al. 1975, *Space Science Instrumentation*, 1, 245
- Blandford, R. D., & Romani, R. W. 1988, *MNRAS*, 234, 57P
- Blumenthal, G. R., & Gould, R. J. 1970, *Rev. Mod. Phys.*, 42, 237
- Bogovalov, S. V., & Aharonian, F. A. 2000, *MNRAS*, 313, 504
- Bradt, H., Rappaport, S., & Mayer, W. 1969, *Nature*, 222, 728
- Browning, R., Ramsden, D., & Wright, P. J. 1971, *Nature Physical Science*, 232, 99
- Burnham, K. P., & Anderson, D. R. 2002, *Model selection and multimodel inference: a practical information-theoretic approach*, 2nd edn. (Springer)
- Burnight, T. 1949, *Phys. Rev*, 76, 19
- Caballero, I., & Wilms, J. 2012, *Mem. Soc. Astron. Italiana*, 83, 230
- Carroll, B. W., & Ostlie, D. A. 2006, *An Introduction to Modern Astrophysics*, 2nd edn. (Benjamin Cummings)
- Cash, W. 1979, *ApJ*, 228, 939

- Castelletti, G., Dubner, G., Golap, K., & Goss, W. M. 2006, *A&A*, 459, 535
- Chandrasekhar, S. 1931, *ApJ*, 74, 81
- Chaves, R. C. G., Renaud, M., Lemoine-Goumard, M., & Goret, P. 2008, in *American Institute of Physics Conference Series*, Vol. 1085, American Institute of Physics Conference Series, ed. F. A. Aharonian, W. Hofmann, & F. Rieger, 372–375
- Chen, A. W., Piano, G., Tavani, M., et al. 2011, *A&A*, 525, A33
- Cocke, W. J., Disney, M. J., & Taylor, D. J. 1969, *Nature*, 221, 525
- Critchfield, C. L., Ney, E. P., & Oleksa, S. 1952, *Physical Review*, 85, 461
- Dame, T. M. 2011, *ArXiv e-prints*
- de Geus, E. J., Bronfman, L., & Thaddeus, P. 1990, *A&A*, 231, 137
- de los Reyes, R., Zajczyk, A., Chaves, R. C. G., & for the H. E. S. S. collaboration. 2012, *ArXiv e-prints*
- de Naurois, M., & H.E.S.S. Collaboration. 2013, *Advances in Space Research*, 51, 258
- Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, *Nature*, 467, 1081
- Djannati-Ataï, A., de Jager, O. C., Terrier, R., & et al. 2008, in *International Cosmic Ray Conference*, Vol. 2, International Cosmic Ray Conference, 823–826
- Eadie, W. T., Drijard, D., & James, F. E. 1971, *Statistical methods in experimental physics* (North-Holland Pub. Co.)
- Espinoza, C. M., Lyne, A. G., Kramer, M., Manchester, R. N., & Kaspi, V. M. 2011, *ApJ*, 741, L13
- Esposito, J. A., Bertsch, D. L., Chen, A. W., et al. 1999, *ApJS*, 123, 203
- Falanga, M., Kuiper, L., Poutanen, J., et al. 2005, *A&A*, 444, 15

- Feenberg, E., & Primakoff, H. 1948, *Phys. Rev.*, 73, 449
- Fichtel, C. E., Hartman, R. C., Kniffen, D. A., et al. 1975, *ApJ*, 198, 163
- Fisher, R. A. 1925, *Statistical Methods for Research Workers* (Edinburgh: Oliver and Boyd)
- Fritz, G., Henry, R. C., Meekins, J. F., Chubb, T. A., & Friedman, H. 1969, *Science*, 164, 709
- Funk, S., Hinton, J. A., Pühlhofer, G., et al. 2007, *ApJ*, 662, 517
- Gaensler, B. M., Schulz, N. S., Kaspi, V. M., Pivovarov, M. J., & Becker, W. E. 2003, *ApJ*, 588, 441
- Gaensler, B. M., & Slane, P. O. 2006, *ARA&A*, 44, 17
- Gaisser, T. K., Protheroe, R. J., & Stanev, T. 1998, *ApJ*, 492, 219
- Gelfand, J. D., Slane, P. O., & Zhang, W. 2009, *ApJ*, 703, 2051
- Giordano, F., & Fermi LAT Collaboration. 2011, in *High-Energy Emission from Pulsars and their Systems*, ed. D. F. Torres & N. Rea, 69
- Gold, T. 1968, *Nature*, 218, 731
- Goldreich, P., & Julian, W. H. 1969, *ApJ*, 157, 869
- Górski, K. M., Hivon, E., Banday, A. J., et al. 2005, *ApJ*, 622, 759
- Gotthelf, E. V., & Halpern, J. P. 2008, *ApJ*, 681, 515
- Grenier, I. A., Casandjian, J.-M., & Terrier, R. 2005, *Science*, 307, 1292
- Grondin, M.-H., Funk, S., Lemoine-Goumard, M., et al. 2011, *ApJ*, 738, 42
- Gunn, J. E., & Ostriker, J. P. 1969, *Nature*, 221, 454
- H. E. S. S. Collaboration, Abramowski, A., Acero, F., et al. 2012, *A&A*, 541, A5

- Hall, T. A., Bond, I. H., Bradbury, S. M., et al. 2003, *ApJ*, 583, 853
- Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, *ApJS*, 123, 79
- Haug, E. 1975, *Zeitschrift Naturforschung Teil A*, 30, 1099
- Hayakawa, S. 1952, *Progress of Theoretical Physics*, 8, 571
- Herschel, W. 1800, *Philosophical Transactions of the Royal Society of London*, 90, pp. 284
- H.E.S.S. Collaboration, Abramowski, A., Acero, F., et al. 2011a, *A&A*, 531, A81
- . 2011b, *A&A*, 528, A143
- H.E.S.S. Collaboration, Acero, F., Aharonian, F., et al. 2011c, *A&A*, 525, A45
- H.E.S.S. Collaboration, Abramowski, A., Acero, F., et al. 2011d, *A&A*, 533, A103
- . 2011e, *A&A*, 525, A46
- Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. 1968, *Nature*, 217, 709
- Hewitt, J., Grondin, M.-H., Lemoine-Goumard, M., et al. 2012
- Hofverberg, P. 2011, in *International Cosmic Ray Conference*, Vol. 7, *International Cosmic Ray Conference*, 247
- Hoppe, S. 2008, in *International Cosmic Ray Conference*, Vol. 2, *International Cosmic Ray Conference*, 579–582
- Houck, J. C., & Allen, G. E. 2006, *ApJS*, 167, 26
- Hulsizer, R. I., & Rossi, B. 1948, *Phys. Rev.*, 73, 1402
- Hutchinson, G. 1952, *Philosophical Magazine Series 7*, 43, 847
- Hwang, U., Petre, R., & Flanagan, K. A. 2008, *ApJ*, 676, 378

- James, F., & Roos, M. 1975, *Computer Physics Communications*, 10, 343
- Jansky, K. 1933, *Proceedings of the Institute of Radio Engineers*, 21, 1387
- Kargaltsev, O., Pavlov, G. G., & Wong, J. A. 2008, ArXiv e-prints
- Kaspi, V. M., & Helfand, D. J. 2002, in *Astronomical Society of the Pacific Conference Series*, Vol. 271, *Neutron Stars in Supernova Remnants*, ed. P. O. Slane & B. M. Gaensler, 3
- Katagiri, H., Tibaldo, L., Ballet, J., et al. 2011, *ApJ*, 741, 44
- Katsuta, J., Uchiyama, Y., Tanaka, T., et al. 2012
- Kennel, C. F., & Coroniti, F. V. 1984, *ApJ*, 283, 710
- Kerr, M. 2010, PhD thesis, University of Washington
- King, I. 1962, *AJ*, 67, 471
- Klein, O., & Nishina, T. 1929, *Zeitschrift fur Physik*, 52, 853
- Kniffen, D. A., & Fichtel, C. E. 1970, *ApJ*, 161, L157
- Krause, J., Carmona, E., Reichardt, I., & for the MAGIC Collaboration. 2011, ArXiv e-prints
- Kraushaar, W., Clark, G. W., Garmire, G., et al. 1965, *ApJ*, 141, 845
- Kraushaar, W. L., Clark, G. W., Garmire, G. P., et al. 1972, *ApJ*, 177, 341
- Landi, R., de Rosa, A., Dean, A. J., et al. 2007a, *MNRAS*, 380, 926
- Landi, R., Masetti, N., Bassani, L., et al. 2007b, *The Astronomer's Telegram*, 1047, 1
- Large, M. I., Vaughan, A. E., & Mills, B. Y. 1968, *Nature*, 220, 340
- Li, T.-P., & Ma, Y.-Q. 1983, *ApJ*, 272, 317

- Longair, M. S. 2011, *High Energy Astrophysics*, 3rd edn. (The Edinburgh Building, Cambridge CB2 8RU, UK: Cambridge University Press)
- Markwardt, C. B., & Ogelman, H. 1995, *Nature*, 375, 40
- Matsumoto, H., Ueno, M., Bamba, A., et al. 2007, *PASJ*, 59, 199
- Matsumoto, H., Uchiyama, H., Sawada, M., et al. 2008, *PASJ*, 60, 163
- Mattox, J. R., Bertsch, D. L., Fichtel, C. E., et al. 1992, *ApJ*, 401, L23
- Mattox, J. R., Bertsch, D. L., Chiang, J., et al. 1996, *ApJ*, 461, 396
- Mayer-Hasselwander, H. A., Kanbach, G., Bennett, K., et al. 1982, *A&A*, 105, 164
- McArthur, S. 2011, *ArXiv e-prints*
- McK Mahille, J., Schild, R., Wendorf, F., & Brenner, R. 2007, *African Skies*, 11, 2
- Mizukami, T., Kubo, H., Yoshida, T., et al. 2011, *ApJ*, 740, 78
- Morrison, P. 1958, *Il Nuovo Cimento*, 7, 858
- Murphy, T., Mauch, T., Green, A., et al. 2007, *MNRAS*, 382, 382
- Neronov, A., Semikoz, D. V., Tinyakov, P. G., & Tkachev, I. I. 2011, *A&A*, 526, A90
- Nolan, P. L., Arzoumanian, Z., Bertsch, D. L., et al. 1993, *ApJ*, 409, 697
- Nolan, P. L., Fierro, J. M., Lin, Y. C., et al. 1996, *A&AS*, 120, C61
- Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, *ApJS*, 199, 31
- Pacini, F. 1967, *Nature*, 216, 567
- . 1968, *Nature*, 219, 145
- Pacini, F., & Salvati, M. 1973, *ApJ*, 186, 249
- Paron, S., Dubner, G., Reynoso, E., & Rubio, M. 2008, *A&A*, 480, 439

- Petre, R., Becker, C. M., & Winkler, P. F. 1996, *The Astrophysical Journal Letters*, 465, L43
- Pollock, A. M. T. 1985, *A&A*, 150, 339
- Protassov, R., van Dyk, D. A., Connors, A., Kashyap, V. L., & Siemiginowska, A. 2002, *ApJ*, 571, 545
- Rea, N., & Esposito, P. 2011, in *High-Energy Emission from Pulsars and their Systems*, ed. D. F. Torres & N. Rea, 247
- Rees, M. J., & Gunn, J. E. 1974, *MNRAS*, 167, 1
- Renaud, M., Goret, P., & Chaves, R. C. G. 2008, in *American Institute of Physics Conference Series*, Vol. 1085, *American Institute of Physics Conference Series*, ed. F. A. Aharonian, W. Hofmann, & F. Rieger, 281–284
- Reynoso, E. M., Dubner, G. M., Goss, W. M., & Arnal, E. M. 1995, *AJ*, 110, 318
- Reynoso, E. M., Green, A. J., Johnston, S., et al. 2003, *MNRAS*, 345, 671
- Richards, D. W., & Comella, J. M. 1969, *Nature*, 222, 551
- Rodriguez, J., Tomsick, J. A., Foschini, L., et al. 2003, *A&A*, 407, L41
- Rousseau, R., Grondin, M.-H., Van Etten, A., et al. 2012, *A&A*, 544, A3
- Rowell, G., Horns, D., Fukui, Y., & Moriguchi, Y. 2008, in *American Institute of Physics Conference Series*, Vol. 1085, *American Institute of Physics Conference Series*, ed. F. A. Aharonian, W. Hofmann, & F. Rieger, 241–244
- Rybicki, G. B., & Lightman, A. P. 1979, *Radiative processes in astrophysics* (New York: John Wiley & Sons Ltd)
- Schwarz, G. 1978, *The Annals of Statistics*, 6, pp. 461
- Sheidaei, F. 2011, in *International Cosmic Ray Conference*, Vol. 7, *International Cosmic Ray Conference*, 243

- Slane, P., Castro, D., Funk, S., et al. 2010, *The Astrophysical Journal*, 720, 266
- Sreekumar, P., Bertsch, D. L., Hartman, R. C., Nolan, P. L., & Thompson, D. J. 1999, *Astroparticle Physics*, 11, 221
- Sreekumar, P., Bertsch, D. L., Dingus, B. L., et al. 1992, *ApJ*, 400, L67
- Sreekumar, P., Bertsch, D. L., Dingus, B. L., et al. 1998, *The Astrophysical Journal*, 494, 523
- Staelin, D. H., & Reifstein, III, E. C. 1968, *Science*, 162, 1481
- Strong, A. W., & Moskalenko, I. V. 1998, *ApJ*, 509, 212
- Sugizaki, M., Mitsuda, K., Kaneda, H., et al. 2001, *ApJS*, 134, 77
- Swanenburg, B. N., Hermsen, W., Bennett, K., et al. 1978, *Nature*, 275, 298
- Swanenburg, B. N., Bennett, K., Bignami, G. F., et al. 1981, *ApJ*, 243, L69
- Tanaka, T., Allafort, A., Ballet, J., et al. 2011, *ApJ*, 740, L51
- Taylor, A. R., Gibson, S. J., Peracaula, M., et al. 2003, *AJ*, 125, 3145
- Terrier, R., Mattana, F., Djannati-Atai, A., et al. 2008, in *American Institute of Physics Conference Series*, Vol. 1085, *American Institute of Physics Conference Series*, ed. F. A. Aharonian, W. Hofmann, & F. Rieger, 312–315
- Thompson, D. J. 2008, *Reports on Progress in Physics*, 71, 116901
- Thompson, D. J., Fichtel, C. E., Hartman, R. C., Kniffen, D. A., & Lamb, R. C. 1977a, *ApJ*, 213, 252
- Thompson, D. J., Fichtel, C. E., Kniffen, D. A., & Ogelman, H. B. 1977b, *ApJ*, 214, L17
- Thompson, D. J., Bertsch, D. L., Fichtel, C. E., et al. 1993, *ApJS*, 86, 629
- Tomsick, J. A., Lingenfelter, R., Walter, R., et al. 2003, *IAU Circ.*, 8076, 1

Torii, K., Kinugasa, K., Toneri, T., et al. 1998, *ApJ*, 494, L207

van der Swaluw, E., & Wu, Y. 2001, *ApJ*, 555, L49

Vladimirov, A. E., Digel, S. W., Jóhannesson, G., et al. 2011, *Computer Physics Communications*, 182, 1156

Weekes, T. C., Cawley, M. F., Fegan, D. J., et al. 1989, *ApJ*, 342, 379

Weinstein, A., & for the VERITAS Collaboration. 2009, *ArXiv e-prints*

Young, E. T., Lada, C. J., & Wilking, B. A. 1986, *ApJ*, 304, L45