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Pulsars and their nebulae as EGRET sources

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Abstract

At the end of the EGRET mission, only 6–8 Galactic sources had been identified as young pulsars. Since then, several energetic pulsars have been detected in EGRET error boxes along the Galactic plane, as well as several pulsar wind nebulae from which pulsations have not yet been discovered. Some of these nebulae are associated with moderately variable EGRET sources, suggesting that the γ-ray emission might be coming from the nebula rather than from the pulsar magnetosphere. There is also a population of unidentified EGRET sources at mid-Galactic latitudes which have been proposed to be either nearby middle-aged pulsars or millisecond pulsars. I review the current status of observational studies of pulsars associated with EGRET sources and what they suggest the upcoming AGILE and GLAST γ-ray missions might observe.

Keywords: Pulsars; Pulsar wind nebulae; EGRET; γ-Ray sources

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1. The EGRET legacy

The EGRET instrument (1991–1999) on board the Compton Gamma-Ray Observatory produced the best data currently available on the 30 MeV–20 GeV sky. It detected nearly 300 (Hartman et al., 1999; Lamb and Macomb, 1997) discrete sources of high-energy γ-rays. The EGRET sources seem to have at least three spatial distributions. There is a nearly isotropic population, nearly all ($\sim$100) of which have now been plausibly associated with blazars, a radio bright sub-class of active galactic nuclei (Sowards-Emmerd et al., 2003, 2004; Mattox et al., 2001). There is a population of bright sources with generally hard spectra within a few degrees of the Galactic plane. Six to eight of these have been identified as young, energetic pulsars by direct detection of γ-ray pulsations at periods previously known through radio or X-ray observations (Kaspi et al., 2000; Ramanamurthy et al., 1996; Nolan et al., 1996). These pulsars all have fairly hard γ-ray spectra (photon power-law index $\Gamma \lesssim 2.2$) and their emission averaged over many pulsations is very steady. The existence of Geminga, a nearby γ-ray pulsar from which there has been no confirmed detection of radio pulsations despite many extensive searches, and the spatial coincidence of unidentified EGRET sources with regions of recent star formation (Kaaret and Cottam, 1996; Yadigaroglu and Romani, 1997; Romero et al., 1999) suggest many of the unidentified sources could be young pulsars not previously detected, or even undetectable, in radio. However, the $\log N - \log S$ distribution of the unidentified sources is not the same as that of young pulsars (Bhattacharya et al., 2003), and many of the sources show evidence for variability (McLaughlin et al., 1996; Nolan et al., 2003), indicating more than one source class (see Table 1).

There is a third population of sources at mid-Galactic latitudes ($5° \lesssim b \lesssim 30°$) which is fainter and which generally have steeper spectra than the low-latitude sources. The spatial distribution is similar to that of the collec-

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Table 1
Known and potential EGRET pulsars and PWN

Name	3EG Name	Type[a]	$\log \dot{E}$	Γ[b]	ζ[c]	V_{12}[d]	δ[d]
CTA 1	3EG J0010 + 7309	?	–	1.85 ± 0.10	–	0.40	$0.26^{+0.47}_{-0.26}$
PSR J0218 + 4232	3EG J0222 + 4253	M	35.4	2.6[e]	–	–	$0.0^{+0.37}_{-0.00}$
Crab	3EG J10534 + 2200	S	38.7	2.19 ± 0.02	62°	–	$0.08^{0.07}_{0.05}$
Geminga	3EG J0633 + 1751	R	34.5	1.66 ± 0.01	–	–	$0.10^{0.06}_{0.04}$
Vela	3EG J0834 – 4511	S	36.8	1.69 ± 0.01	64°	0.61	$0.16^{0.12}_{0.06}$
PSR, J1016-5857	3EG J1013 – 5915	?	36.4	2.32 ± 0.13	–	0.18	$0.14^{0.38}_{0.14}$
PSR B1046-58	3EG J1048 – 5840	?	36.3	1.97 ± 0.09	–	–	$0.0^{+0.31}_{0.00}$
PSR B1055-52	3EG J1058 – 5234	?	34.5	1.94 ± 0.10	–	–	$0.0^{0.47}_{0.00}$
PSR J1420-6048	3EG J1420 – 6038	?	37.0	2.02 ± 0.14	–	1.59	$1.03^{0.80}_{0.66}$
Rabbit	3EG J1420 – 6038	R	–	2.02 ± 0.14	–	1.59	$1.03^{0.80}_{0.66}$
PSR J1614-2230	3EG J1616 – 2221	M	34.1	2.42 ± 0.24	–	–	$0.0^{0.54}_{0.00}$
PSR B1706-44	3EG J1710 – 4439	S	36.5	1.86 ± 0.04	55°	–	$0.07^{0.14}_{0.07}$
G359.89-0.08	3EG J1746 – 2851	R	–	1.70 ± 0.07	–	2.35	$0.48^{0.27}_{0.19}$
G7.4-2.0	3EG J1809 – 2328	R	–	2.06 ± 0.08	–	3.93	$0.71^{0.42}_{0.25}$
G18.5-0.4	3EG J11826 – 1302	R	–	2.00 ± 0.11	–	3.22	$0.88^{0.57}_{0.38}$
RX J1836.2 + 5925	3EG J11835 + 5918	G	–	1.69 ± 0.07	–	0.09	$0.15^{0.32}_{0.15}$
PSR J1837-0604	3EG J1837 – 0606	–	36.3	1.82 ± 0.14	–	–	$0.0^{0.67}_{0.00}$
PSR B1853 + 01	3EG J1856 + 0114	R	35.6	1.93 ± 0.10	–	1.57	$0.71^{0.82}_{0.43}$
PSRB 1951 + 32	–[f]	R	36.6	1.7 ± 0.1	–	–	–
PSR J2021 + 3651	3EG J2021 + 3716	S	36.5	1.86 ± 0.10	83°	0.71	$0.36^{0.47}_{0.33}$
PSR J2229 + 6114	3EG J2227 + 6122	S	37.4	2.24 ± 0.14	46°	0.21	$0.02^{0.62}_{0.20}$

[a] R = RPWN, S = SPWN, ? = PWN type unclear, G = Possible Gould Belt, M = MSP.

[b] EGRET photon spectral index (from Hartman et al., 1999, save where noted).

[c] Spin axis inclination angle (Ng and Romani, 2004; Hessels et al., 2004).

[d] Variability indices from (Nolan et al., 2003) – see text.

[e] Estimated contribution from pulsar (see Kuiper et al., 2000, for details).

[f] Only seen in pulsations (Ramanamurthy et al., 1996).

tion of nearby regions of recent star formation known as the Gould belt, with possibly the addition of a halo population (Grenier, 2001). However, it is also similar to the distribution of millisecond pulsars (Romani, 2001) and there was one marginal detection of pulsed emission from the millisecond pulsar PSR J0218 + 4232 in the EGRET data (Kuiper et al., 2000).

Here I will discuss observational progress that has been made since the demise of CGRO in the study of pulsars as sources of the emission detected by EGRET. These studies are preparing the ground for future γ-ray missions such as AGILE and GLAST. For a recent review of high-energy emission from pulsars and their nebulae, see Kaspi et al. (2004).

2. High resolution X-ray imaging of γ-ray pulsars: Constraining the geometry

Energetic pulsars accelerate particles to high energies in their magnetospheres. These particles can interact with the surrounding medium to produce synchrotron nebulae which are bright in radio and X-rays (for references to individual nebulae, see the on-line Pulsar Wind Nebula (PWN) Catalog at http://www.physics.mcgill.ca/~pulsar/pwncat.html). Around the youngest, most energetic sources, the radio emitting parts of these nebulae tend to be rather amorphous, but the X-ray emitting regions can be highly structured. The high spatial resolution of the *Chandra* satellite has allowed these structures to be resolved. The three youngest (characteristic age $\tau < 20{,}000$ years) γ-ray emitting pulsars, Crab, Vela, and PSR B1706 –44, all have toroidal nebulae with perpendicular jets. The tori are presumably produced by equatorial winds, while the jets are aligned with the spin axes. The middle aged pulsar ($\tau \sim 100{,}000$ years) PSR B1951 + 32 has a RPWN which is distorted by the pulsar's motion, while the two oldest pulsars ($\tau > 300{,}000$ years), PSR B1055-52 and Geminga, have very faint PWN.

The location of the particle accelerating region in the magnetosphere is still being debated (see eg. Daugherty and Harding, 1996; Romani, 1996; Harding and Muslimov, 1998, and elsewhere in these proceedings). The polar cap class of models presume the emission is from a region near the magnetic Poles, the outer gap class of models assume the emission comes from near the light cylinder, while the more recent slot gap models bridge the two regions. All of the models in principle can predict the shape of the γ-ray pulse profile, given the overall geometry of the pulsar: i.e. the viewing angle between the spin axis and the observer (ζ) and the magnetic inclination angle between the spin axis and the magnetic axis. The outer gap models have been fairly successful in reproducing the observed γ-ray pulse profiles (Romani and Yadigaroglu, 1995), but the geometry was, in