EGRET Observations of Pulsars

1. Introduction

EGRET continues to observe rotation-powered pulsars in the 30 MeV – 20 GeV gamma-ray band. So far six have been positively detected. The most recent addition to the list is PSR B1951+32, which is discussed by Ramanamurthy et al. 1996 (see also Brazier et al. 1994, Ramanamurthy et al. 1995). It joins the Crab, Vela, Geminga, PSR B1706−44 and PSR B1706−44. Upper limits for emission from many other pulsars have been published (Thompson et al. 1994; Fierro et al. 1995).

Table 1 lists the parameters of the detected high-energy gamma-ray pulsars, including the spin period $P$, dispersion measure distance $D$, inferred surface magnetic field $B_s$, and spin-down energy loss rate $\dot{E}$. In general, the pulsars that are detected are the ones that should be expected. One can construct a list of pulsars ordered by $\dot{E}/D^2$ (Fierro 1995). Five of the six detected pulsars are found at the top of this list, along with PSR B1509−58, which is detected at $\sim$1 MeV. Only PSR B1055−52 appears much farther down the list.

There are three sources in the second EGRET catalog (Thompson et al. 1995) which are coincident with the positions of pulsars high on the $\dot{E}/d^2$ list, PSR B1509−58, PSR B1823−13 and PSR B1853+01. No pulsation at the proper period has yet been detected from any of these. All three are rather noisy pulsars, so their ephemerides are not as accurate as might be desired (Kaspi et al. 1994; Lyne et al. 1992). Also they are in regions of low EGRET exposure and fairly high gamma-ray background.

Table 1. Parameters of the High-Energy Gamma-Ray Pulsars

| Pulsar       | $P$ (ms) | $D$ (km) | $B_s$ ($10^{12}$ G) | $\dot{E}$ (ergs s$^{-1}$) |
|--------------|----------|----------|---------------------|---------------------------|
| Crab         | 33.4     | 2.0      | 3.7                 | $4.5 \times 10^{38}$      |
| Geminga      | 237.1    | 0.25     | 1.6                 | $3.3 \times 10^{34}$      |
| Vela         | 89.3     | 0.50     | 3.3                 | $6.9 \times 10^{36}$      |
| PSR B1055−52 | 197.1    | 1.5      | 1.1                 | $3.0 \times 10^{34}$      |
| PSR B1706−44 | 102.4    | 1.8      | 3.1                 | $3.4 \times 10^{36}$      |
| PSR B1951+32 | 39.5     | 2.5      | 0.48                | $3.7 \times 10^{36}$      |

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2. Continuous emission

Figure 1 shows the light curves for >100 MeV gamma rays from the three brightest pulsars, Crab, Vela, and Geminga. A logarithmic scale is used to allow the low flux values to be visible. To produce these curves, spatial photon maps were made for each of twenty equal-width bins in pulsar phase. For each phase interval, the source flux was found using a maximum-likelihood technique which searches for a point-source excess above a structured background (Mattox et al. 1996). This method removes any contribution from the diffuse emission near the pulsar’s position. This should be compared with the older method (Nolan et al. 1993; Kanbach et al. 1994; Bertsch et al. 1992; Mayer-Hasselwander et al. 1994), in which the total number of photons is counted in each phase bin; the lowest value is assumed to be the background contribution, which can then be subtracted from the others. The older method implicitly assumes that the pulsar shuts off its gamma-ray emission for a substantial portion of each rotation.

The Crab light curve shows the well-known two peaks and a lower level of emission throughout the rotation. Note that the flux never drops to zero. It has been traditional to assume that the weak off-pulse emission between phase 0.5 and 0.9 is due solely to the Crab Nebula, which EGRET cannot spatially resolve from the pulsar (Nolan et al. 1993; Clear et al. 1987). This tradition can be attributed to an analogy with the behavior in the X-ray band, where the pulsar and nebula can be spatially resolved (Harnden & Seward 1984). The X-ray pulsar emission drops to nearly zero for much of each rotation while the nebula continues to shine brightly.

Vela, the next youngest gamma-ray pulsar, shows a similar pattern. Unlike the Crab pulsar, however, the bridge emission between the two peaks remains at a very high level. Still, there is detectable emission through at least 95% of the rotation. In previous analysis (Kanbach et al. 1994), it has been assumed that the pulsar shuts off for about 40% of each rotation. The detected emission in the off-pulse phase interval is sufficiently weak that the conclusions of the analysis are still valid.

Geminga (Mayer-Hasselwander et al. 1994) shows the same pattern. It emits through the entire rotation, with strong bridge emission, and an off-pulse emission level above that from the Crab. This is troubling because Geminga is over 10^5 years old, much too old to have a dense synchrotron/Compton nebula like the Crab’s.

If that is the case, could not the same be true for the Crab? The belief in the Crab’s nebular emission must be called into doubt. Since the Crab Nebula is certainly there, it must emit gamma rays at some level. The best we can say is that the detected off-pulse gamma flux is an upper limit on the nebular emission.

3. Average spectra

The average spectra of the six EGRET-detected pulsars are shown in Figure 2. In this analysis, the spectra are derived by the maximum-likelihood spatial analysis. In detail these spectra are slightly different from those derived from the pulse/off-pulse subtraction method. The gross features, though, are unchanged.

Over at least part of the EGRET energy range, each spectrum can be described quite well by a simple power law. The fitted (number) spectral indices range from −2.07 for the Crab to −1.39 for Geminga. With additional data available, the index for PSR B1055-52 is found to be −1.50±0.13, softer than originally reported, but still quite hard. Indeed, four of the six spectra have indices harder than −1.6, which may be significant for emission models.

Three of the spectra show clear evidence for a drop in flux at high energy, above a few GeV. Two others have large uncertainties in the 4–10 GeV band, and cannot ex-
Crab Pulsar

| Energy (MeV) | Photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ |
|-------------|-------------------------------------|
| 10-13       | $10^{-12}$                           |
| 10-12       | $10^{-11}$                           |
| 10-11       | $10^{-10}$                           |
| 10-10       | $10^{-9}$                            |
| 10-9        | $10^{-8}$                            |
| 10-8        | $10^{-7}$                            |
| 10-7        | $10^{-6}$                            |

α = -2.07 ± 0.03

Vela Pulsar

| Energy (MeV) | Photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ |
|-------------|-------------------------------------|
| 10-13       | $10^{-12}$                           |
| 10-12       | $10^{-11}$                           |
| 10-11       | $10^{-10}$                           |
| 10-10       | $10^{-9}$                            |
| 10-9        | $10^{-8}$                            |
| 10-8        | $10^{-7}$                            |
| 10-7        | $10^{-6}$                            |

α = -1.54 ± 0.01

Geminga Pulsar

| Energy (MeV) | Photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ |
|-------------|-------------------------------------|
| 10-13       | $10^{-12}$                           |
| 10-12       | $10^{-11}$                           |
| 10-11       | $10^{-10}$                           |
| 10-10       | $10^{-9}$                            |
| 10-9        | $10^{-8}$                            |
| 10-8        | $10^{-7}$                            |
| 10-7        | $10^{-6}$                            |

α = -1.39 ± 0.02

PSR B1706-44

| Energy (MeV) | Photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ |
|-------------|-------------------------------------|
| 10-13       | $10^{-12}$                           |
| 10-12       | $10^{-11}$                           |
| 10-11       | $10^{-10}$                           |
| 10-10       | $10^{-9}$                            |
| 10-9        | $10^{-8}$                            |
| 10-8        | $10^{-7}$                            |
| 10-7        | $10^{-6}$                            |

α = -1.56 ± 0.05

PSR B1055-52

| Energy (MeV) | Photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ |
|-------------|-------------------------------------|
| 10-13       | $10^{-12}$                           |
| 10-12       | $10^{-11}$                           |
| 10-11       | $10^{-10}$                           |
| 10-10       | $10^{-9}$                            |
| 10-9        | $10^{-8}$                            |
| 10-8        | $10^{-7}$                            |
| 10-7        | $10^{-6}$                            |

α = -1.50 ± 0.13

PSR B1951+32

| Energy (MeV) | Photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ |
|-------------|-------------------------------------|
| 10-13       | $10^{-12}$                           |
| 10-12       | $10^{-11}$                           |
| 10-11       | $10^{-10}$                           |
| 10-10       | $10^{-9}$                            |
| 10-9        | $10^{-8}$                            |
| 10-8        | $10^{-7}$                            |
| 10-7        | $10^{-6}$                            |

α = -1.78 ± 0.09

Fig. 2. Average photon number spectra of the six pulsars detected by EGRET. Each can be fitted by a power law over part of the energy range.

4. Light curve shapes

The gamma-ray light curves of the three weaker pulsars are shown in Figure 3. It is possible to draw some general conclusions from these curves and from Figure 1.

Fig. 3. Light curves of the three weaker pulsars. The main radio pulse occurs at phase 0.

The most obvious feature of the light curves is that four of them have two roughly equal peaks separated by 0.4–0.5 in phase. The other two, PSR B1055–52 (Fierro et al. 1993) and PSR B1706–44 (Thompson et al. 1992), have broad pulses that might really be double or even triple. The suggested narrow peak at phase 0.4 in PSR B1055–52 is not statistically significant. The apparent triple feature of PSR B1706–44 is persistent if the data set is divided in half according to time or photon energy, but it is still too early to determine whether this feature is real. Only improved counting statistics will improve our understanding of these two pulsars.

Double peaks and broad pulses are fairly rare in radio light curves. Of these six pulsars, only the Crab has a gamma-ray light curve which matches fairly well with the radio pulsation, although the radio emission has a third
A peak apparent below 600 MHz that doesn’t match any gamma-ray feature. PSR B1055–52 has a similar triple-peaked radio pulse, but there does not appear to be a correlation between any of the radio and gamma-ray peaks. The three other radio pulsars have single radio peaks which don’t line up with the gamma-ray peaks.

With the limited statistics available, it is impossible to detect any emission between the two peaks of PSR B1951+32. The two peaks are separated by very nearly 0.5 in phase, so it remains unknown which peak should be called the leading and which is the trailing.

5. Trends

In an attempt to better understand the mechanism responsible for gamma-ray pulsation, it is natural to examine possible relationships between the measured gamma-ray characteristics and the inferred pulsar parameters. With the detection of a sixth high-energy gamma-ray pulsar, as well as additional exposure to the other pulsars, some of the trends suggested by early EGRET results stand to be revisited.

One of the more promising trends established by the first five EGRET pulsar detections was an apparent increase in gamma-ray efficiency with pulsar characteristic age (Thompson et al. 1994). The gamma-ray efficiency of a pulsar is defined as the fraction of its available spin-down power which is emitted in the form of high-energy gamma rays. Figure 4 shows an updated plot of the gamma-ray efficiency versus characteristic age, where it has been arbitrarily assumed that the gamma rays are beamed into a solid angle of 1.0 steradian. Based on the original five EGRET pulsars, it does indeed seem that older pulsars convert more of their luminosity into gamma rays.

However, the gamma-ray efficiency of PSR B1951+32 deviates by an order of magnitude from the power law trend established by the other pulsars, far more than can be reasonably attributed to differences in pulsar beaming angles. Only the Crab has a measured efficiency which is below that of PSR B1951+32. Thus, the presumption that gamma-ray efficiency increases with characteristic age would appear not to hold true in all cases.

Thompson et al. (1994) also noted that among the original five EGRET pulsars, the derived photon spectral indices were harder for the older pulsars. However, additional data has shown that the spectra of at least three pulsars have high-energy turnovers (see Figure 2) which cannot be fit by a single power-law over the entire EGRET energy range. Restricting the spectral fit to the energy range over which the pulsar emission is consistent with a power law shows that Vela, PSR B1706-44, and PSR B1055-52 have consistent spectral indices. In addition, PSR B1951+32 has a softer spectral index than the younger pulsars Vela and PSR B1706-44. So there does not seem to be a correlation between spectral hardness and characteristic age.

It is noteworthy that at least five of the high-energy gamma-ray pulsars have light curves exhibiting more than one peak, and the sixth pulsar has insufficient statistics to resolve the pulse morphology. This suggests that multiple-peak pulse profiles are a natural consequence of gamma-ray emission from pulsars.

Double-peaked emission patterns are not unexpected in current models of gamma ray production from pulsars (e.g. Daugherty & Harding 1981; Dermer & Sturmer 1994; Yadigaroglu & Romani 1995). Models should now also address the strong bridge emission—as well as the sizeable off-pulse emission—evident from the three brightest gamma-ray pulsars.

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