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EGRET HIGH-ENERGY γ-RAY PULSAR STUDIES. II. INDIVIDUAL MILLISECOND PULSARS

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ABSTRACT

More than 2 yr of observations performed by the Energetic Gamma Ray Experiment Telescope (EGRET) aboard the *Compton Gamma Ray Observatory* (*CGRO*) are examined for evidence of high-energy γ-ray emission from individual millisecond pulsars. Upper limits are placed on steady emission. In addition, for those millisecond pulsars for which an accurate timing solution is available, upper limits to pulsed γ-ray emission are established. The results are compared with predictions of current pulsar γ-ray emission models. In particular, the absence of a detection of γ-rays from the nearby millisecond pulsar PSR J0437−4715 severely constrains theories regarding γ-ray emission from millisecond pulsars.

Subject headings: gamma rays: observations — pulsars: general

1. INTRODUCTION

With their rapid rotation periods and correspondingly weaker magnetic field strengths, millisecond pulsars (MSPs) have proved to be a distinct class of radio pulsars and must be considered separately from the "normal" radio pulsar population. It is widely believed that MSPs are formed when a neutron star begins to accrete from a low-mass companion. This system evolves into a low-mass X-ray binary (LMXB) in which the pulsar spins up due to the accreted angular momentum, eventually producing a pulsar with a period of a few milliseconds and a weak surface magnetic field of 10^8–10^9 G (e.g., Bhattacharya & van den Heuvel 1991). Grindlay & Bailyn (1988) have suggested an alternative scenario in which MSPs result from an accretion-induced collapse of massive white dwarfs in binary systems. In either case, it is expected that globular cluster cores with their high stellar densities will produce a large number of accreting binary systems and thus contain more MSPs.

There are two types of high-energy γ-ray emission which might be expected from MSPs, namely, radiation from the pulsar magnetosphere and emission resulting from the pulsar wind interacting with the surrounding medium. Six pulsars have been detected as γ-ray emitters by *CGRO* (Thompson et al. 1994), five of which are detectable by EGRET. These pulsars all have relatively small characteristic ages and have periods ranging from 33 to 237 ms, with inferred surface magnetic fields in excess of 10^{12} G. Current theoretical models suggest that pulsed γ-rays are the result of radiation from charged particles which are accelerated in the pulsar magnetosphere (e.g., Harding 1981; Cheng, Ho, & Ruderman 1986). Although the derived characteristics such as apparent age and surface magnetic field for MSPs differ by ~4 orders of magnitude from those of the known γ-ray pulsars, the properties of the magnetospheres of MSPs are predicted to be qualitatively similar to the outer magnetosphere of Vela-like pulsars (Ruderman & Cheng 1988), so it is not unreasonable to expect magnetospheric γ-ray emission from MSPs.

A rough measure of the potential visibility of a pulsar at the Earth is $\dot{E}/d^2$, where $\dot{E}$ is the rotational energy loss rate and d is the distance to the pulsar. Since $\dot{E}$ is proportional to $\dot{P}/P^3$, where P and $\dot{P}$ are the rotational period and period derivative of the pulsar, this measure can be easily determined from observable quantities. Ranking the 558 pulsars listed in Taylor, Manchester, & Lyne (1993) by this measure reveals that five of the six detected γ-ray pulsars fall among the top 10 pulsars, while PSR B1055−52 places twenty-fifth on the list. In Paper I of this series, Thompson et al. (1994) search for high-energy γ-ray emission from those young radio pulsars with the 40 highest values of $\dot{E}/d^2$. However, since the MSPs PSR J0437−4715, B1937+21, B1821−24, B1957+20, J0034−0534, and B1257+12 all have values of $\dot{E}/d^2$ greater than that of the γ-ray pulsar PSR B1055−52, it is also necessary to consider possible γ-ray emission from MSPs. Indeed,

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TABLE 1

MILLISECOND PULSAR OBSERVED AND DERIVED PARAMETERS

PSR (Globular Cluster)	Period (ms)	B_s (10^8 G)	Distance (kpc)	Binary	Exposure (>100 MeV) (10^8 cm^2 s)	Reference
B0021−72C (47 Tucanae)	5.76	...	4.5		6.80	
B0021−72D (47 Tucanae)	5.36	...	4.6		6.80	
B0021−72E (47 Tucanae)	3.54	...	4.5	Yes	6.80	
B0021−72F (47 Tucanae)	2.62	...	4.5		6.80	
B0021−72G (47 Tucanae)	4.04	...	4.5		6.80	
B0021−72H (47 Tucanae)	3.21	...	4.5	Yes	6.80	
B0021−72I (47 Tucanae)	3.48	...	4.5	Yes	6.80	
B0021−72J (47 Tucanae)	2.10	...	4.5	Yes	6.80	
B0021−72L (47 Tucanae)	4.35	...	4.5		6.80	
B0021−72M (47 Tucanae)	3.68	...	4.5		6.80	
J0034−0534	1.88	1.1	1.0	Yes	1.89	1
J0437−4715	5.76	3.4[a]	0.1	Yes	4.77	
J0613−0200	3.06	3.5	2.2	Yes	6.90	2
J0751+18	3.48	...	2.0	Yes	3.22	3
J1045−4509	7.47	3.8	3.2	Yes	5.96	1
B1257+12	6.22	4.9[a]	0.6	Yes	8.79	
J1455−3330	7.99	...	0.7	Yes	7.73	2
B1516+02A (M5)	5.55	5.8	7.0		3.85	
B1516+02B (M5)	7.95	...	7.0	Yes	3.85	
B1620−26 (M4)	11.08	30	1.8	Yes	10.13	
B1639+36A (M13)	10.38	...	7.7		4.26	
B1639+36B (M13)	3.53	...	7.7	Yes	4.26	
J1643−1224	4.62	3.9	>4.9	Yes	8.73	2
J1713+0747	4.57	1.9	0.9	Yes	3.21	4
J1730−2304	8.12	5.2	0.5		12.53	2
B1744−24A (Terzan 5)	11.56	...	7.1	Yes	12.59	
B1802−07 (NGC 6539)	23.10	33	3.1	Yes	9.06	
B1820−30A (NGC 6624)	5.44	...	8.0		11.73	
B1821−24 (M28)	3.05	22	5.5		11.48	
B1855+09	5.36	3.1[a]	1.0	Yes	6.37	
B1908+00 (NGC 6760)	3.60	...	4.1	Yes	7.74	
B1937+21	1.56	4.0[a]	3.6		8.72	
B1953+29	6.13	4.3	5.4	Yes	10.24	
B1957+20	1.61	1.4[a]	1.5	Yes	8.31	
J2019+2425	3.93	1.2[a]	0.9	Yes	8.90	
B2127+11D (M15)	4.80	...	10.0		3.74	
B2127+11E (M15)	4.65	9.1	10.0		3.74	
B2127+11F (M15)	4.03	3.6	10.0		3.74	
B2127+11H (M15)	6.74	4.0	10.0		3.74	
J2145−0750	16.05	6.3	0.5	Yes	4.40	1
J2317+1439	3.45	1.3	1.9	Yes	3.76	5
J2322+2057	4.81	0.73[a]	0.8		3.31	

[a] Denotes magnetic fields adjusted for Shklovskii effect (Camilo et al. 1994; Bell et al. 1995).

REFERENCES.—All pulsar parameters are from Taylor et al. 1993, except (1) Bailes et al. 1994; (2) Lorimer et al. 1995; (3) Lundgren 1994; (4) Foster et al. 1993; (5) Camilo et al. 1993.

not only does PSR J0437−4715 have the seventh highest value of $\dot{E}/d^2$, but it has also recently been confirmed as a pulsed X-ray source (Becker & Trümper 1993), the first MSP to be detected outside of the radio frequency range. Observed values of the γ-ray efficiency η_γ for converting the total pulsar spin-down power $\dot{E}$ into γ-rays above 100 MeV range from 10^{-4} to almost unity (Fierro et al. 1993). It is therefore conceivable that for a reasonably high value of η_γ, EGRET could detect pulsed γ-radiation from an isolated MSP. This is particularly intriguing in view of the fact that the γ-ray pulsars with larger characteristic ages have demonstrated higher γ-ray efficiencies.

X-rays and γ-rays generated by the interaction of the relativistic pulsar wind with either the surrounding medium or the evaporating material from a companion star are expected to be unpulsed (Kluzniak et al. 1988; Phinney et al. 1988; Tavani 1991; Arons & Tavani 1993). This process is most probable in those MSPs which show evidence of eclipsing. Based on theoretical models, this type of emission from a single MSP is not expected to be above the EGRET detection threshold (Arons & Tavani 1993). Since this paper is only concerned with γ-ray emission from individual MSPs, this process will not be considered here. However, considering that some of the more dense globular clusters may contain several hundred MSPs (Kulkarni, Narayan, & Romani 1990), it is not unreasonable to expect that their net γ-ray emission may be detectable by EGRET. The search for collective γ-ray emission from MSPs in globular clusters using EGRET observations is presented by Michelson et al. (1994) in a separate paper.

2. OBSERVATIONS

EGRET is sensitive to γ-rays in the energy range from approximately 30 MeV to 30 GeV. Descriptions and general capabilities of the instrument are given by Hughes et al. (1980), Kanbach et al. (1988, 1989), Nolan et al. (1992), and Thompson et al. (1993). EGRET records each γ-ray as an electron-positron pair production event. This event is processed automatically, with manual verification for questionable events, to determine the optimal estimate of arrival direction and energy of the photon (Bertsch et al. 1989). The arrival time of each photon is recorded in Universal Coordinated Time (UTC) with an absolute timing accuracy of better than 100 μs. Because of the very low flux level of high-energy γ-rays, observing periods are typically ~2 weeks.

The observations considered here were part of an all-sky survey carried out by EGRET during Phase I (1991 April to 1992 November) and Phase II (1992 November to 1993 September) of the *CGRO* mission. The exposure to the sky is not uniform, with particular concentration along the Galactic plane, and the γ-ray diffuse background is extremely non-isotropic (Bertsch et al. 1993), resulting in a higher sensitivity to some MSP candidates than to others. Table 1 lists the measured and derived characteristics of the MSPs considered in this paper, along with the EGRET exposure above 100 MeV to each MSP. Here, MSPs are defined to be those radio pulsars with rotation periods less than 30 ms. The inferred surface magnetic field B_s is derived from the relation $B_s \approx 3.2 \times 10^{19}(P\dot{P})^{1/2}$, so to properly determine the intrinsic magnetic field, it is necessary to know the intrinsic period derivative $\dot{P}_i$, which is not necessarily identical to the measured period derivative $\dot{P}_m$. Shklovskii (1970) showed that for a pulsar with transverse speed v at a distance d, an apparent acceleration will result in a $\dot{P}_m$ related to $\dot{P}_i$ by

$$\dot{P}_m \approx \dot{P}_i + \frac{Pv^2}{cd} , \qquad (1)$$

where c is the speed of light. For the small $\dot{P}$ associated with MSPs, this effect becomes quite significant, particularly for those nearby pulsars (Camilo, Thorsett, & Kulkarni 1994). Pulsar distance estimates are obtained from applying the Taylor & Cordes (1993) distance model to the observed dispersion measures. Estimates from this model are accurate to within ~25%. The EGRET exposure to each source was calculated from the known telescope sensitivity as a function of operating mode and energy (Thompson et al. 1993) and the known times of occultations and live time of the instrument.

3. RESULTS

3.1. *Unpulsed Emission*

Each of the five γ-ray pulsars detected above 100 MeV was first seen as a high-energy γ-ray point source (Kniffen et al. 1974; Fichtel et al. 1975; Thompson et al. 1977; Swaneburg et al. 1981; Fierro et al. 1993). Hence, one indication of pulsed or unpulsed emission from an MSP would be a γ-ray excess at the known location of the radio pulsar. A maximum likelihood analysis (Mattox et al. 1995) of the spatial distribution of the EGRET data was employed to search for γ-ray emission from the known MSPs. The γ-ray background over the EGRET energy range is assumed to consist of an isotropic, extragalactic component and Galactic diffuse emission due primarily to cosmic-ray particles interacting with matter and fields in the Galaxy (Bertsch et al. 1993; Sreekumar et al. 1995). Source fluxes are derived using the detector point-spread function to model any excess detected above the predicted γ-ray background. Nearby point sources are also included in the expected background so as not to affect the flux estimate from the MSP.

The 3 σ (99.87% confidence) upper limits to the unpulsed γ-ray flux are listed in Table 2 for three energy ranges: $30 < E_\gamma < 100$ MeV, $E_\gamma > 100$ MeV, and $E_\gamma > 1$ GeV. The sensitivity of EGRET to a candidate source will be adversely affected by the γ-ray emission from a strong point source which is in close spatial proximity. Considering that PSR B1620−26 is ~1° from the quasar PKS 1622−253, the globular cluster M13 is ~2° from the quasar 4C 38.41, and PSR J1730−2304 and B1744−24A are each ~2°.5 from the EGRET source GRO J1741−22, it is difficult to place stringent upper limits to γ-ray emission from these MSPs. The known radio position of PSR B1953+29 fell within the 95% confidence contour of a 3 σ excess detected above 100 MeV, which is not remarkable in light of the fact that this pulsar was discovered while searching for counterparts of the γ-ray point sources identified by the European satellite *COS B* (Boriakoff, Buccheri, & Fauci 1983). No other positionally coincident γ-ray excesses were detected above a significance of 3 σ in any of the three energy ranges.

TABLE 2

UPPER LIMITS TO UNPULSED γ-RAY EMISSION FROM MSPs

Object	3 σ Flux Upper Limits (10^{-8} photons cm^{-2} s^{-1})		
	30–100 MeV	>100 MeV	>1 GeV
47 Tucanae	42.4	5.0	0.9
PSR J0034−0534	120.1	15.2	5.3
PSR J0437−4715	84.4	15.1	2.0
PSR J0613−0200	51.5	15.8	2.8
PSR J0751+18	81.8	21.9	3.3
PSR J1045−4509	58.2	8.4	2.2
PSR B1257+12	35.9	4.0	0.8
PSR J1455−3330	59.9	11.7	2.0
M5	57.6	9.1	2.5
PSR B1620−26[a]	104.9	9.4	1.2
M13[b]	66.6	15.2	1.8
PSR J1643−1224	69.6	19.7	2.2
PSR J1713+0747	136.0	16.8	1.8
PSR J1730−2304[c]	66.8	10.5	1.3
PSR B1744−24A[c]	153.1	15.6	3.8
PSR B1802−07	141.9	21.1	0.8
PSR B1820−30A	92.5	8.5	1.6
PSR B1821−24	110.9	16.1	1.5
PSR B1855+09	106.6	18.2	2.6
PSR B1908+00	169.2	13.7	1.2
PSR B1937+21	69.8	15.1	2.6
PSR B1953+29	70.8	27.8	2.8
PSR B1957+20	63.2	16.8	2.9
PSR J2019+2425	61.6	11.5	1.1
M15	65.6	8.1	2.7
PSR J2145−0750	50.7	6.6	1.8
PSR J2317+1439	77.1	10.8	2.7
PSR J2322+2057	61.2	8.8	1.4

[a] Near γ-ray source PKS 1622−253.
[b] Near γ-ray source 4C 38.41.
[c] Near γ-ray source GRO J1741−22.

There was no significant excess apparent near PSR J0751+18, even though this pulsar was discovered while searching the error box of an EGRET excess detected in one of the earliest observations with a reported significance of 4.6 σ (Lundgren 1994). A refined analysis of the original Phase I observation reveals the actual significance of this excess to be slightly less than 3 σ, and subsequent EGRET observations of this location show no indication of a γ-ray excess. Thus, it appears that PSR J0751+18 is not associated with a known γ-ray point source and instead is a purely fortuitous discovery.

3.2. *Pulsed Emission*

To search for modulation of the γ-ray light curve at the period of the radio pulsation, it is necessary to have an accurate timing ephemeris valid over the length of the *CGRO* observation. As part of a coordinated program involving radio astronomers and the *CGRO* instrument teams, a large fraction of the known radio pulsars are being monitored on a regular basis to provide contemporary pulsar ephemerides. Unfortunately, nearly all of the pulsars in globular clusters are distant and weak, making high-precision timing measurements difficult or impossible. Furthermore, the gravitational field of globular clusters can have a perturbing effect (Blandford, Romani, & Applegate 1987), further complicating the determination of timing solutions. Hence, long-term solutions are more readily obtainable for MSPs outside of globular clusters. Fortunately, recent successes of pulsar searches (Johnston et al. 1993; Nice, Taylor, & Fruchter 1993; Foster, Wolszczan, & Camilo 1993; Camilo, Nice, & Taylor 1993; Lundgren 1994; Bailes et al. 1994; Lorimer et al. 1995) have increased the number of known field MSPs from five to 18.

In an attempt to optimize the signal-to-noise ratio, events were selected from an energy-dependent cone of half-angle $\theta_{\max} = 5^\circ\!.85 \times (E_\gamma/100\ \mathrm{MeV})^{-0.534}$, with photon energy E_γ in MeV, about the known position of each candidate pulsar. This cone accepts $\sim 67\%$ of the photons detected by EGRET from a point source (Thompson et al. 1993). In addition, to eliminate Earth albedo γ-rays at a 4 σ confidence level, only those γ-rays arriving within a zenith angle $\psi \leq 110^\circ - 4\theta_{\max}$ were used. The arrival times of the selected γ-rays were transformed to solar system barycentric time, and the corresponding pulsar phase ϕ was calculated by taking the fractional part of the Taylor expansion

$$\phi(T) = \nu T + \tfrac{1}{2}\dot{\nu}T^2 + \tfrac{1}{6}\ddot{\nu}T^3 , \tag{2}$$

where ν, $\dot{\nu}$, and $\ddot{\nu}$ are the pulsar spin frequency and first two derivatives measured at the reference epoch T_0, and the pulsar proper time $T = t_b - T_0$ is the time elapsed between the reference epoch and γ-ray barycentric arrival time t_b. For MSPs in a binary system, the significant acceleration of the pulsar due to orbital motion called for an additional transformation to determine the pulsar proper time in a nonaccelerating reference frame (Blandford & Teukolsky 1976).

The resulting phase distribution was examined for evidence of periodicity using the H-test (De Jager, Swanepoel, & Raubenheimer 1988), which does not rely on binning. In this method, a test statistic H is defined as

$$H = \max_{1 \leq m \leq 20} (Z_m^2 - 4m + 4) , \tag{3}$$

where

$$Z_m^2 = \frac{2}{N} \sum_{j=1}^{m} \left\{ \left[\sum_{i=1}^{N} \cos (2\pi j \phi_i) \right]^2 + \left[\sum_{i=1}^{N} \sin (2\pi j \phi_i) \right]^2 \right\} , \tag{4}$$

with the N pulsar phases ϕ_i determined from equation (2). The calculated value of H is used to compute the probability that the pulsar phases ϕ_i are drawn from a uniform phase distribution. The definition of H in equation (3) essentially optimizes the number of harmonics m based on the data, making the H-test a powerful means of examining the data for a wide range of possible light-curve shapes. For the 19 MSPs for which there is an available ephemeris, no significant evidence of pulsation was found.

Since the H-test does not assume a specific light-curve shape, it does not lend itself well to direct construction of upper limits to the pulsar signal strength, although De Jager (1994) has proposed a method to calculate such flux limits. Alternatively, it is possible to establish conservative upper limits from the Rayleigh test by assuming that the pulsar light curve has a normalized sinusoidal phase distribution of the form

$$f(\phi) = 1 + a \cos 2\pi(\phi - \phi_0) , \tag{5}$$

with a representing the fraction of the photon events that are pulsed. The probability of measuring a Rayleigh power Z_1^2 from this distribution is (Protheroe 1987)

$$p(Z_1^2 \,|\, a) = \tfrac{1}{2} e^{-Z_1{}^2/2 - Na^2/4} I_0(a Z_1 \sqrt{N/2}) , \tag{6}$$

where I_0 is the zeroth-order modified Bessel function of the first kind and $Z_1 \equiv (Z_1^2)^{1/2}$. To establish upper limits to the number of pulsed counts aN, it is necessary to know the probability of having a pulsed fraction a given the measured Z_1^2. According to Bayes's theorem,

$$p(a \,|\, Z_1^2) = \frac{p(Z_1^2 \,|\, a) w(a)}{\int_0^1 p(Z_1^2 \,|\, a') w(a')\, da'} , \tag{7}$$

where $w(a)$ is the expected distribution of a. For simplicity, a uniform probability $w(a) = 1$ for $0 \leq a \leq 1$ is assumed. Although this is not a very realistic prior assumption as it implies that an entirely pulsed signal is equally as likely as a completely unpulsed signal, it will produce reasonably conservative upper limits (see discussion in appendix of De Jager 1994). The upper limit to the pulsed fraction a_{ul} can now be obtained by solving

$$C = \int_0^{a_{\mathrm{ul}}} p(a' \,|\, Z_1^2) da' = \frac{\int_0^{a_{\mathrm{ul}}} e^{-Na'^2/4} I_0(a' Z_1 \sqrt{N/2})\, da'}{\int_0^1 e^{-Na'^2/4} I_0(a' Z_1 \sqrt{N/2})\, da'} , \tag{8}$$

where C is the required confidence level (i.e., 99.87% for a 3 σ upper limit). The pulsed count upper limits are divided by the 0.67 acceptance cone fraction and then combined with the exposure to give the flux upper limits. Table 3 lists the total number of events analyzed, the H-test probability of a uniform distribution, and the 3 σ pulsed flux upper limits for each MSP over the energy ranges $30 < E_\gamma < 100$ MeV and $E_\gamma > 100$ MeV. There were too few counts measured above 1 GeV to derive meaningful upper limits; suffice it to say that there was no significant evidence of pulsation over any of the energy ranges analyzed.

Comparison of Table 3 with Table 2 shows that the unpulsed upper limits are generally more restrictive than pulsed upper limits. This is primarily because the unpulsed analysis incorporates a well-established model of the Galactic diffuse γ-ray background and an extragalactic isotropic component matched to the neighboring regions to provide a detailed model of the background above which to look for an excess distributed according to the detector point-spread function, whereas attempting to determine the background level for pulsed analysis suffers from a lack of statistics at γ-ray energies. In addition, an extra degree of freedom is introduced into the pulsed analysis since it is not known at which phase to expect a signal. It is possible to establish more stringent pulsed upper limits by searching for higher Fourier components, but this could produce artificially low upper limits which would be invalid for broadly pulsed signals such as those seen in PSR B1055−52 or B1706−44.

4. DISCUSSION

The only marginal evidence of γ-ray emission from MSPs came from a 3 σ excess coincident with the position of PSR

TABLE 3

UPPER LIMITS TO PULSED γ-RAY EMISSION FROM MSPs

	30–100 MeV			>100 MeV		
PSR	N	H-Test Prob	Flux (3 σ) (10^{-8} cm^{-2} s^{-1})	N	H-Test Prob	Flux (3 σ) (10^{-8} cm^{-2} s^{-1})
J0034−053	188	84.1%	276	84	6.4%	49
J0437−4715......	407	99.1	143	207	93.3	21
J0613−0200......	1555	32.5	218	937	18.3	45
J1045−4509......	845	77.5	187	468	7.2	31
J1455−3330......	1235	22.9	171	645	16.2	26
B1620−26........	2083	66.6	169	1533	53.4	33
J1643−1224......	1544	34.2	199	1056	29.2	27
J1713+0747......	554	93.8	241	306	91.0	39
J1730−2304......	5426	45.0	216	4041	71.2	40
B1744−24A......	6982	27.7	306	7635	68.4	55
B1821−24........	5485	74.5	237	3890	14.2	58
B1855+09........	2613	61.8	296	2666	42.8	73
B1937+21........	2807	94.9	196	3073	38.3	58
B1953+29........	3192	40.0	233	3285	46.0	50
B1957+20........	2433	61.9	221	1878	96.8	36
J2019+2425......	2295	66.8	201	1591	24.2	44
J2145−0750......	365	52.9	173	158	19.6	27
J2317+1439......	435	51.8	227	217	62.8	32
J2322+2057......	311	91.6	183	169	42.2	35

B1953+29. This excess measures a γ-ray flux $F = (1.8 \pm 0.6) \times 10^{-7}$ photons cm^{-2} s^{-1} above 100 MeV. If it is assumed this flux is entirely due to PSR B1953+29, then the implied luminosity for a beaming angle of 1.0 sr is $L_\gamma = (3.2 \pm 1.1) \times 10^{34}$ ergs s^{-1}, which is almost an order of magnitude greater than the available spindown power $\dot{E} = 4.6 \times 10^{33}$ ergs s^{-1}. Barring an extremely small beaming angle, this implies the γ-ray excess near PSR B1953+29 is not associated with the pulsar. Hence, no evidence of γ-ray emission from MSPs has been detected by EGRET during the first two phases of operation.

In the absence of a positive detection, the upper limits can be compared to predictions from theoretical models. In the outer gap model (Cheng et al. 1986), γ-rays are produced by primary $e^\pm$ accelerated in vacuum gaps in the outer magnetosphere of the pulsar. Chen & Ruderman (1993) estimate that the γ-ray luminosity L_γ for MSPs is such that the efficiency $\eta_\gamma \equiv L_\gamma/\dot{E}$ has a roughly constant value of 10^{-2} for periods P much less than the death line defined by $P_{\rm death} = 3.5 \times 10^{-3}(B/10^8)^{5/12}$ s, where B is the surface magnetic field in gauss. As MSPs approach this death line, the efficiency increases sharply until the vacuum gaps become quenched above $P_{\rm death}$ and outer magnetosphere pair production ceases. High-energy γ-ray emission in this scenario is thus most likely for energetic pulsars near the death line.

According to the polar cap model (Harding 1981), γ-rays are the result of cascades initiated by the curvature radiation from charged particles accelerated along open magnetic field lines just above the polar cap surface. Harding numerically calculated the spectra above 100 MeV for a range of pulsar periods and magnetic fields and found that the integrated spectra scaled as $\dot{N} \propto B^{0.95}P^{-1.7}$. Normalizing this law to the Crab γ-ray flux of 2.2×10^{-6} photons cm^{-2} s^{-1} observed by EGRET over Phases I and II (Thompson et al. 1995) gives a photon luminosity above 100 MeV of

$$\dot{N}_{\rm polar} \sim 1.3 \times 10^{22} B^{0.95} P^{-1.7} \text{ photons s}^{-1} . \quad (9)$$

Although it may seem unreasonable to expect the polar cap scaling law to be valid for the weak magnetic fields and short periods associated with MSPs, Chiang & Romani (1992) specifically calculated the polar cap emission expected from recycled pulsars and found a dependence on B and P similar to that of Harding (1981). Sturner & Dermer (1994) propose another scenario for polar cap emission in which γ-rays are produced from a nearly aligned pulsar via a resonant Compton-induced pair cascade. Extending their model to MSPs, they predict a total luminosity of

$$L_{\rm SD} = 1.1 \times 10^{10} B^{3/2} P^{-3} \text{ ergs s}^{-1} . \quad (10)$$

Table 4 compares the various predictions of MSP γ-ray flux with the measured 3 σ flux upper limits from Table 2. The

TABLE 4

PREDICTED AND OBSERVED FLUXES ABOVE 100 MeV
(in 10^{-8} cm^{-2} s^{-1})

PSR	$F_{\rm outer}$	$F_{\rm polar}$	$F_{\rm SD}$	$F_{3\sigma}$
J0034−0534......	1.1	0.3	0.04	15.2
J0437−4715......	5.6	22	1.2	15.1
J0613−0200......	0.3	0.1	0.02	15.8
J1045−4509......	0.0	0.04	0.002	8.4
B1257+12........	0.4	1.5	0.09	4.0
B1516+02A......	0.007	0.02	0.001	9.1
B1620−26........	0.2	0.7	0.05	9.4
J1713+0747......	0.1	0.4	0.02	16.8
J1730−2304......	0.0	1.9	0.09	10.5
B1802−07........	0.0	0.2	0.005	21.1
B1821−24........	1.9	0.1	0.05	16.1
B1855+09........	0.1	0.4	0.02	18.2
B1937+21........	2.2	0.1	0.03	15.1
B1953+29........	0.005	0.02	0.001	27.8
B1957+20........	1.3	0.2	0.03	16.8
J2019+2425......	1.7	0.2	0.01	11.5
B2127+11E......	0.02	0.01	0.002	8.1
B2127+11F......	0.005	0.006	0.0005	8.1
B2127+11H......	0.04	0.005	0.0002	8.1
J2145−0750......	0.0	1.5	0.03	6.6
J2317+1439......	0.03	0.07	0.004	10.8
J2322+2057......	0.0	0.2	0.006	8.8

predicted flux F can be calculated from the γ-ray luminosity by using the relation

$$F = \frac{L}{\langle E_\gamma \rangle \Delta\Omega d^2}\,, \qquad (11)$$

where $\langle E_\gamma \rangle$ is the average photon energy, $\Delta\Omega$ is the beaming solid angle, and d is the distance to the pulsar. The average photon energy $\langle E_\gamma \rangle$ was calculated assuming a constant spectral index of -2.0 from 100 MeV to 5 GeV. The beaming solid angle for polar cap emission is $\Delta\Omega = 2\pi[1 - \cos(3\theta_{\rm pc}/2)]$, where $\theta_{\rm pc}$ is the polar cap angle defined as $\sin\theta_{\rm pc} = [2\pi a/(Pc)]^{1/2}$ for a pulsar of radius a and period P. Assuming a typical neutron star radius of 10^6 cm, the MSPs considered here have a polar cap beaming solid angle $\Delta\Omega \approx 0.1$–1.0 sr. There is no consensus as to the outer gap beaming angle, with estimates ranging from 1.0–2π sr. In this paper it is assumed that outer gap radiation is emitted into a broad beam of $\Delta\Omega = 2\pi$ sr.

From Table 4 it can be seen that, except for the polar cap prediction for PSR J0437−4715, the predicted fluxes are well below the measured 3 σ upper limits. It is not surprising that the best test of MSP γ-ray emission models comes from PSR J0437−4715. With its close proximity to the Earth, the expected flux levels for PSR J0437−4715 will be comparatively higher, yet it is located in a region of the sky with relatively little background, so it is possible to establish more restrictive upper limits on its γ-ray flux. Although both the outer gap model and the model of Sturner & Dermer list PSR J0437−4715 as the MSP with the highest flux level, neither model predicts a level of emission detectable by EGRET. In fact, the flux estimates from these models are generally well below the EGRET threshold for detection, so it is doubtful that these models will ever be seriously tested by EGRET observations. The polar cap flux expected from PSR J0437−4715 slightly exceeds the observed upper limit. Considering the assumptions made with regard to the overall normalization and beaming angle, and the ~25% error associated with distance estimates, it would be premature to say whether the polar cap model of Harding (1981) is invalid for MSPs.

Since PSR J0437−4715 has one of the highest values of $\dot{E}/d^2$, the lack of a detection by EGRET implies that it is not very efficient at converting its available rotational energy into γ-rays. The efficiency upper limit for PSR J0437−4715 corresponding to a narrow beaming angle of 1.0 sr is $\eta_{3\sigma} = 4.3 \times 10^{-3}$, which means it can be no more efficient than the Vela pulsar with only the Crab pulsar having an efficiency well below this upper limit (Fierro et al. 1993). This is in contrast to the *ROSAT* X-ray results, which show PSR J0437−4715 to have a total X-ray efficiency comparable to that of Vela and PSR B1706−44 among others (Becker & Trümper 1993). Even though X-ray emission has been detected from all six γ-ray pulsars, this example demonstrates that X-ray emission is not necessarily a definite indicator of γ-ray emission. The same can be said for pulsars with a high value of $\dot{E}/d^2$. Rather, it appears that there is no simple predictor for high-energy γ-ray emission. Future EGRET observations should improve the upper limits established in this paper and further constrain the models of γ-ray emission from MSPs. Particularly important will be the analysis of 3 weeks of on-axis observations of PSR J0437−4715 completed during 1994 June and 1994 July.

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