THE ASTROPHYSICAL JOURNAL, 435:218–224, 1994 November 1

EGRET UPPER LIMITS TO THE HIGH-ENERGY GAMMA-RAY EMISSION FROM THE MILLISECOND PULSARS IN NEARBY GLOBULAR CLUSTERS

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Received 1993 October 26; accepted 1994 May 5

ABSTRACT

We report upper limits to the high-energy gamma-ray emission from the millisecond pulsars (MSPs) in a number of globular clusters. The observations were done as part of an all-sky survey by the Energetic Gamma Ray Experiment Telescope (EGRET) on the *Compton Gamma Ray Observatory* (*CGRO*) during Phase I of the *CGRO* mission (1991 June to 1992 November).

Several theoretical models suggest that millisecond pulsars (MSPs) may be sources of high-energy gamma radiation emitted either as primary radiation from the pulsar magnetosphere or as secondary radiation generated by conversion into photons of a substantial part of the relativistic $e^{\pm}$ pair wind expected to flow from the pulsar. To date, no high-energy emission has been detected from an individual MSP. However, a large number of MSPs are expected in globular cluster cores where the formation rate of accreting binary systems is high. Model predictions of the total number of pulsars range in the hundreds for some clusters. These expectations have been reinforced by recent discoveries of a substantial number of radio MSPs in several clusters; for example, 11 have been found in 47 Tucanae (Manchester et al.).

The EGRET observations have been used to obtain upper limits for the efficiency η of conversion of MSP spin-down power into hard gamma rays. The upper limits are also compared with the gamma-ray fluxes predicted from theoretical models of pulsar wind emission (Tavani). The EGRET limits put significant constraints on either the emission models or the number of pulsars in the globular clusters.

Subject headings: gamma rays: observations — globular clusters: general — pulsars: general

1. INTRODUCTION

Observations with instruments on the *Compton Observatory* (Gehrels, Chipman, & Kniffen 1993) have increased the number of pulsars known to be gamma-ray emitters to six (Kniffen et al. 1993; Fierro et al. 1993; Wilson et al. 1993). They are PSR 0531+21 (Crab), PSR 0833−45 (Vela), PSR 0630+178 (Geminga), PSR 1706−44, PSR 1509−58, and PSR 1055−52. All but one of these sources (PSR 1509−58; Wilson et al. 1993) has been seen by the Energetic Gamma Ray Experiment Telescope (EGRET) at energies above 100 MeV. All of them are relatively young pulsars with periods between 33 and 237 ms and surface magnetic fields, inferred from their periods and period derivatives, in excess of 10^{12} G. The efficiency η for conversion of spin-down power into hard gamma rays ($E > 100$ MeV) ranges from $\sim 10^{-4}$ for the Crab to near unity for Geminga and PSR 1055−52, showing an increase with pulsar period (Fierro et al. 1993).

Millisecond pulsars (MSPs) are members of an older population of neutron stars, characterized by much weaker surface magnetic fields (10^8–10^{10} G) and smaller rotation periods (1.5 to ~ 10 ms) than their younger, higher field cousins. In most scenarios, MSPs are assumed to be the end products of low-mass X-ray binary (LMXB) evolution, in which a neutron star with a weak magnetic field is spun up to a millisecond period during an accretion phase (see review by Bhattachraya & van den Heuvel 1991). Alternatively, Grindlay & Bailyn (1988) have proposed that MSPs result from the accretion-induced collapse of massive white dwarfs in binary systems. In either case, a relatively large number of MSPs are expected to be found in the dense cores of globular clusters where the birth rate of accreting binary systems is likely to be high because of the high stellar densities. Several theoretical estimates have been made of the number of pulsars in globular clusters (Kulkarni, Narayan, & Romani 1990; Wijers & van Paradjis 1991; Johnston, Kulkarni, & Phinney 1992; Tavani 1993). The numbers are highly uncertain. For example, Kulkarni et al. estimate a total population of 10^4 recycled pulsars in globular clusters. Tavani estimates 266 pulsars in the core of 47 Tucanae. We note that recently Chen, Middleditch, & Ruderman (1993) have questioned both of the above scenarios for MSP formation in globular clusters. These authors argue that in most globular cluster LMXBs, the neutron star is born rapidly spinning and that the LMXBs are likely to be decendants, rather than the progenitors, of weakly magnetized MSPs.

Observationally, the first MSP found in a globular cluster (M28) was PSR 1821−24 (Lyne et al. 1987). This was followed by discoveries of many more MSPs in globular clusters. For example, Manchester et al. (1990, 1991) have reported 11 MSPs in 47 Tuc. All of the 47 Tuc pulsars have periods less

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than 6 ms, and nearly half of them are in binary systems. As indicated by their binary orbit parameters, at least two of these systems, PSR 0021−72J and PSR 0021−72E, have low-mass companions (Manchester et al. 1991). Eclipses indicate that the companion of PSR 0021−72J is probably being ablated by radiation from the pulsar. Such eclipses were first observed in PSR 1957+20 (Fruchter et al. 1990) and have also been observed in PSR 1744+24A in Terzan 5 (Lyne et al. 1990; Nice et al. 1990). PSR 1744−24A shows episodes of total radio eclipse. These star-vaporizing pulsars (SVPs) were anticipated theoretically by Ruderman, Shaham, & Tavani (1989).

The expected gamma-ray luminosity from MSPs has been the subject of much theoretical interest, with predictions being made based primarily on extrapolations of models developed for much younger pulsars such as Crab and Vela. This is despite the tremendous differences in surface magnetic fields and spin periods. The two most prominent such models are the polar cap model (Harding 1981), wherein the emission takes place in a charge-depleted region above the magnetic polar caps of the neutron star, and the outer gap models (Cheng, Ho, & Ruderman 1986), in which the site of the emission is a charge-depleted accelerator gap that forms above the last closed magnetic field line and extends out to near the velocity of light cylinder. In both models the gamma-ray luminosity is dependent on the period and period derivative. While it is not at all clear whether the emission mechanisms in these models apply to millisecond pulsars, there is no clear reason to eliminate them either. For example, Ruderman & Cheng (1988) have argued that the outer magnetosphere of the MSP may not differ much from that of a young pulsar, with comparable total magnetospheric voltage drop and magnetic field strength near the light cylinder for both classes of pulsars. Chiang & Romani (1992) have made predictions for the gamma-ray emission from globular clusters based on the polar cap model and the cluster population model of Kulkarni et al. (1990). Independent of the validity of any of the emission models, if a MSP at the distance of 47 Tuc (4.6 kpc), with a typical surface magnetic field value of 3×10^8 G, emitted $\sim 1\%$ of its spin-down luminosity in the form of gamma rays above 100 MeV, the flux at Earth would be $\sim 10^{-8}$ photon cm^{-2} s^{-1}, below the EGRET detection threshold. Thus it is not surprising that a single MSP has not yet been detected as a pulsed high-energy gamma-ray source.

Following the discovery of eclipses in several binary systems containing MSPs, several authors have considered the possibility that gamma rays might also be created through the interaction of the expected relativistic (TeV) $e^{\pm}$ wind from the pulsar with the surrounding medium or with a mass outflow from the companion star in the case of a binary (Kluzniak et al. 1988; Phinney et al. 1988; Tavani 1991; Arons & Tavani 1993). Specifically, Kluzniak et al. (1988) and Phinney et al. (1988) have suggested that in a binary system like PSR 1957+20, the TeV particle energy in the pulsar wind can be converted into high-energy photons, by either synchrotron radiation or inverse Compton scattering from low-energy background photons, at the shock interface between the pulsar wind and the mass outflow from the companion. Most recently, Arons & Tavani (1993) have modeled in detail the emission arising from such a relativistic shock. Based on these theoretical models, Tavani (1993) has predicted that even a single hidden SVP may be detected in a number of relatively nearby (within 5.2 kpc) globular clusters. However, the expected gamma-ray fluxes are highly dependent on details of the models.

The discovery of many MSPs in the core of the globular cluster 47 Tuc, predicted gamma-ray fluxes for individual MSPs, the predictions that the total number of such objects in any one cluster might be in the hundreds, have motivated us to analyze EGRET observations of a number of globular clusters for evidence of the collective gamma-ray emission from pulsars in these clusters. In this paper we also discuss the implications for emission models and the number of pulsars in these clusters. The observations were part of an all-sky survey by EGRET during Phase I of the *Compton Observatory* mission (1991 June to 1992 November).

2. OBSERVATIONS

EGRET is sensitive to gamma rays in the energy range from ~ 30 MeV to 30 GeV. In the mode used for most of the observations reported here the effective area of the telescope is ~ 1000 cm^2 at 150 MeV and 1500 cm^2 around 0.5–1 GeV for targets near the center of the field of view. The instrument has components typically used in high-energy gamma-ray telescopes; an anticoincidence system to discriminate against charged particle radiation, a multilevel thin-plate spark chamber system to convert gamma rays and determine the trajectories of the secondary electron-positron pair, a triggering telescope that detects the presence of the pair with the correct direction of motion, and an energy measuring calorimeter, which in the case of EGRET is a NaI(Tl) crystal. Descriptions of the instrument are given by Hughes et al. (1980) and Kanbach et al. (1988). Details of the instrument calibration, both before and after launch, are given by Thompson et al. (1993) and Nolan et al. (1992). The instrument is carefully designed to be free of internal background and its calibration tests have verified that the internal background is at least an order of magnitude below the extragalactic diffuse gamma radiation.

The angular resolution does not allow any of the observed globular clusters to be resolved in gamma rays. Therefore they are treated as point sources in the analysis. The positions of a cluster is taken as the position of the center of the cluster core. Table 1 summarizes the EGRET observations of each of the globular clusters considered here. The table gives the cluster

TABLE 1

SUMMARY OF EGRET GLOBULAR CLUSTER OBSERVATIONS

Cluster	Position (l, b)	Distance (kpc)	Exposure ($E > 100$ MeV) (10 cm^2 s)
NGC 5139	309°10, 15°0	5.2	5.34
47 Tuc	305.90, −44.9	4.6	5.03
NGC 6656	9.89, −7.6	3.1	8.19
M4	350.97, 16.0	2.1	7.04
NGC 6544	5.84, −2.2	2.6	8.48
NGC 6397	338.16, −12.0	2.2	4.53
NGC 6266	353.57, 7.3	6.1	7.83
NGC 6553	5.25, −3.0	5.7	8.40
NGC 6752	336.50, −25.6	4.1	3.20
NGC 6626	7.80, −5.6	5.8	8.28
NGC 6440	7.73, 3.8	7.1	8.46
Terzan 5	3.84, 1.7	7.1	8.58
NGC 6380	350.30, −3.6	4.0	6.92
Liller 1	354.80, −0.2	7.9	7.86
NGC 2808	282.19, −11.2	9.5	8.90
NGC 6539	20.80, 6.8	3.1	7.48
NGC 6760	36.11, −3.9	4.1	8.36
NGC 6388	345.56, −6.7	13.5	6.04
NGC 6441	353.53, −5.0	11.7	7.36
NGC 6522	1.02, −3.9	6.6	8.46

positions, distances, and the EGRET exposure. In most cases the exposure is the cumulative exposure obtained from several EGRET pointings for each of which the cluster was in the EGRET field of view. Note that EGRET's effective area is maximum when the target is on axis and falls to ~50% of this value when the angular offset reaches 20°. The clusters are ranked according to N_p/d^2, where N_p is the expected number of cluster pulsars and d is the cluster distance. The values of this quantity as calculated by Tavani (1993) are given in column (4) of Table 2. Tavani assumes that the overall number of pulsars in globular clusters is $N_t = 10^4$ (Kulkarni et al. 1990). We report here on the analysis of EGRET observations of the 20 brightest clusters ranked in this way.

A maximum-likelihood method (Mattox et al. 1994) was used to search for a flux from the known position of a globular cluster, consistent with the instrument's point spread function, in excess of that expected from the diffuse background. The method was first applied to *COS B* gamma-ray data by Pollock et al. (1981, 1985). The EGRET likelihood analysis is based upon binned gamma-ray counts maps and corresponding exposure maps that provide the EGRET exposure for each pixel of the counts maps. The method is particularly suited to analysis of fields where the diffuse background has spatial structure.

The likelihood function is defined as

$$L = \prod_i p_i , \tag{1}$$

where p_i is the probability of obtaining the observed counts in the ith pixel of the counts map. This probability is given by the Poisson distribution:

$$p_i = \frac{\theta_i^{n_i} e^{-\theta_i}}{n_i!} , \tag{2}$$

where n_i is the observed number of counts in the ith pixel and θ_i is the predicted number of counts. The product in equation (1) is over all of the pixels in the region of the map being analyzed. The radius of this analysis region is typically 15°. The model for the counts in each pixel is

$$\theta_i = \int_{i\text{th pixel}} [g(\rho)E(\rho) + I\,\text{psf}\,(|\rho - \rho_s|)E(\rho_s)]d\Omega , \tag{3}$$

where $g(\rho)$ is a distribution function which describes the background emission and the contribution from other point sources in the field; I is the intensity of a putative source at position $\rho = \rho_s = (\phi_s, \theta_s)$; $E(\rho)$ is the exposure at ρ; and psf $(|\rho - \rho_s|)$ is the EGRET point spread function for a source at position ρ_s.

The distribution of background photons $g(\rho)$ has several components. For EGRET analysis $g(\rho)$ is

$$g(\rho) = G_m g_D(\rho) + G_b + O_{\text{psf}}(\rho)\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1} , \tag{4}$$

where $g_D(\rho)$ is the distribution function for the galactic diffuse emission determined from the model of Bertsch et al. (1993) and convolved with the EGRET point spread function (see below), G_m is an undetermined normalization, G_b is the isotropic diffuse emission, and $O_{\text{psf}}(\rho)$ is the contribution from other point sources in the field whose contribution is determined by their intensity, position, and the appropriate point spread functions. In practice the parameters G_m, G_b, and I are determined by maximizing the likelihood function. An E^{-2} differential photon spectrum was assumed for the point source in determining the energy-weighted psf.

The significance of a source detection when using the likelihood method is determined by a likelihood ratio test (Eadie et al. 1971; Stuart & Ord 1987). The likelihood test statistic TS is

$$\text{TS} = 2 \log \frac{\max (L_{\text{alt}})}{\max (L_{\text{null}})} , \tag{5}$$

where max (L_{alt}) is the maximized likelihood function over the allowed parameter space including the putative source (alternative hypothesis) and max (L_{null}) is the maximized likelihood for a model without the source (null hypothesis). In the limit of a large number of counts, TS is distributed as χ^2_ν, where ν is the difference in the number of free parameters under the

TABLE 2

95% Confidence Upper Limits for Gamma-Ray Emission above 100 MeV

Cluster (1)	Photon Flux Limit (10^{-8} photons cm^{-2} s^{-1}) (2)	Luminosity (10^{35} ergs s^{-1}) (3)	N_p/d^2 (kpc^{-2}) (4)	Diffuse Background Flux (10^{-4} photons cm^{-2} s^{-1} sr^{-1}) (5)
NGC 5139	17.8	5.3	12.68	0.55
47 Tuc	5.0	1.2	12.61	0.42
NGC 6656	20.1	2.1	11.80	1.3
M4	13.4	0.64	9.98	0.97
NGC 6544	14.6	1.1	8.42	4.9
NGC 6397	22.1	1.2	7.76	0.68
NGC 6266	9.0	3.7	7.60	1.4
NGC 6553	13.1	4.6	6.51	4.2
NGC 6752	11.2	2.1	5.88	0.48
NGC 6626	15.4	5.6	5.61	1.8
NGC 6440	14.2	7.8	5.59	2.8
Terzan 5	26.4	15.0	4.55	4.5
NGC 6380	12.4	2.2	4.36	2.7
Liller 1	23.8	14.0	4.22	6.9
NGC 2808	7.9	7.0	3.62	0.72
NGC 6539	25.2	2.6	3.55	1.9
NGC 6760	12.1	2.2	3.36	2.3
NGC 6388	10.3	10.0	3.24	1.5
NGC 6441	10.1	15.0	2.41	2.1
NGC 6522	11.4	5.4	2.33	3.0

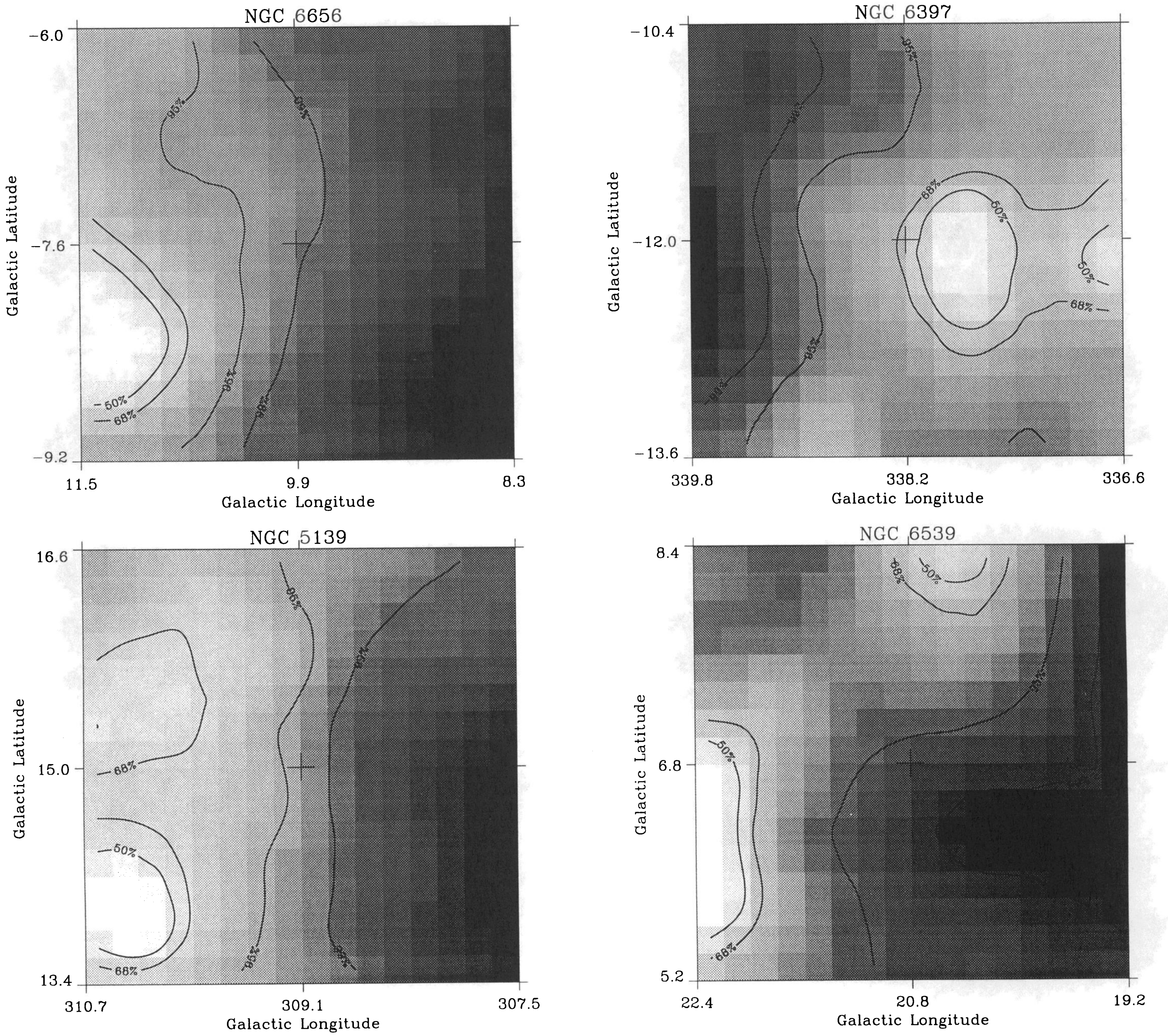

FIG. 1.—Maps of the maximum likelihood test statistic (TS) for clusters NGC 5139, NGC 6656, NGC 6397, and NGC 6539. TS is defined by TS = 2 log [max (L_{alt}/max (L_{null})], where L_{alt} is the likelihood of the model which includes a source at the test position plus the background model and L_{null} is the likelihood for the background model alone. TS defined in this way is distributed as χ^2 with 1 d.o.f. (Stuart & Ord 1987). The cluster position is at the center of each map. The analysis is done for gamma-ray emission above 100 MeV.

alternative hypothesis and the null hypothesis. Thus, for a single point source at a given location, TS is distributed as χ_1^2.

The model of the diffuse gamma-ray background from the galaxy is based on the interaction of cosmic rays with interstellar gas and the interstellar radiation field. The primary gamma-ray production processes are nucleon-nucleon interactions, electron bremsstrahlung, and inverse Compton scattering. The expected diffuse emission is calculated from a detailed knowledge of the interstellar gas together with a model of the cosmic-ray density (Kniffen & Fichtel 1981; Fichtel & Kniffen 1984; Bertsch et al. 1993). The cosmic-ray density is assumed to be almost proportional to the local gas density because of confinement of cosmic rays by interaction with interstellar magnetic fields embedded in the interstellar gas.

Except for NGC 5139, NGC 6656, NGC 6397, and NGC 6539, no significant emission above the 2 σ confidence level was found from any of the globular clusters observed. Upper limits (95% confidence) to the photon flux above 100 MeV for all of these clusters are given in Table 2 along with the corresponding luminosity upper limits, assuming the distances given in Table 1 and isotropic emission. The diffuse background (galactic plus isotropic) flux at the position of each cluster is also given. For each of the four clusters listed above, a detec-

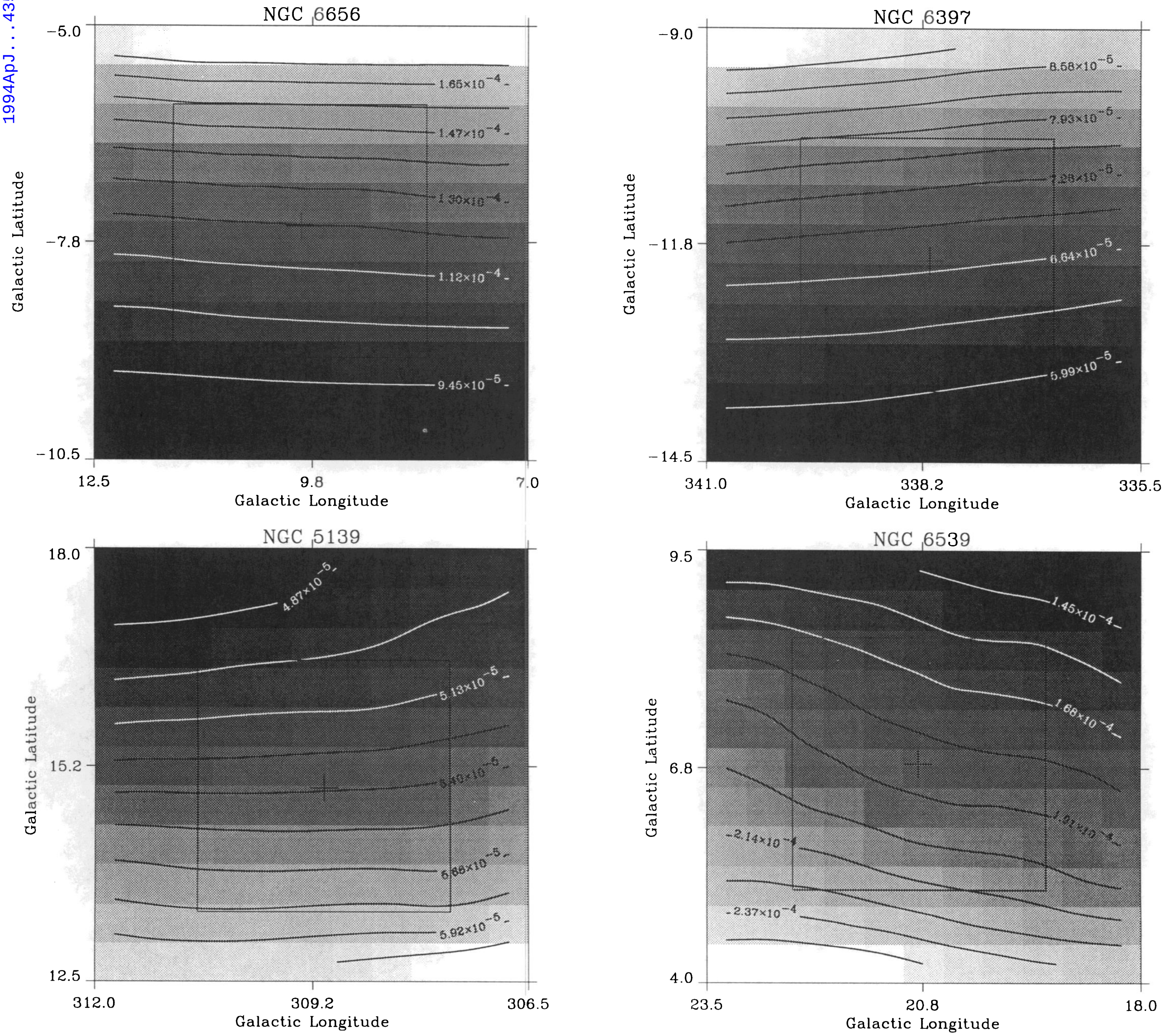

FIG. 2.—Maps of the diffuse gama-ray emission in the vicinity of the cluster locations shown in Fig. 1. These maps are obtained by fitting the diffuse emission model summarized in the text to the EGRET observations for each of the regions shown. The cluster position is at the center of each map.

tion with formal significance between 2.2 σ and 2.7 σ was found. However, the angular resolution of the observations does not exclude the possibility that the fluxes derived at the locations of these clusters may include contributions from other nearby sources which are not accounted for in the likelihood model. An examination of the shape of the maps of the maximum likelihood test statistic, shown in Figure 1, for clusters NGC 5139, NGC 6656, and NGC 6539 indicates that the measured fluxes are likely to be due to other nearby sources of emission. These other sources may be unresolved point sources or extended emission features not included in the galactic diffuse emission model. The data was also examined for evidence of time variability of the emission detected near these four clusters. None was found. The diffuse emission in the regions around each of these clusters, obtained from equation (4), is shown in Figure 2. In any case, no emission consistent with a point source at the location of these clusters is found. For NGC 6397, a peak in the likelihood test statistic consistent with a point source is seen at (LII, BII) = (337°.7, −12°.2), 0°.55 away from the cluster location. NGC 6397 lies outside of the 68% confidence contour for the location of this gamma-ray excess and therefore cannot be identified as the source with very high confidence. Thus we conclude that there is no strong evidence for emission from any of these clusters.

3. DISCUSSION

The EGRET upper limits can be compared with the predicted primary gamma radiation from MSPs, as well as with the radiation expected from the interaction of the pulsar wind with the surrounding medium. Chen (1991) made a comparison, based on *COS B* observations of 47 Tuc, with predictions of the primary MSP radiation. The EGRET upper limits of 47 Tuc are about a factor of 50 below the *COS B* limit (A. Pollock, private communication). Upper limits to the hard X-ray/soft gamma-ray emission (40 to 1200 keV) from 47 Tuc obtained from observations by the SIGMA telescope have recently been reported by Barret et al. (1993). Much of the discussion here follows that of Barret et al. but is extended to the higher energy range of the EGRET observations.

The spin-down power ($I\Omega\dot{\Omega}$) is clearly an upper limit to the gamma-ray luminosity of a pulsar. The magnetospheric efficiency (η) is defined as $\eta = L_\gamma/I\Omega\dot{\Omega}$, where we take L_γ to be the gamma-ray luminosity above 100 MeV. Assuming that the mechanisms responsible for high-energy gamma-ray emission in relatively young pulsars also operate at high spin frequencies and low magnetic fields, then MSPs must also be considered as potential sources of high energy emission. Such arguments have been made for both the polar cap model (Harding 1981; Daugherty & Harding 1982; Chiang & Romani 1993) and the outer gap model (Cheng, Ho, & Ruderman 1986; Ruderman & Cheng 1988). In a recent consideration of the outer gap model, Chen & Ruderman (1993) have argued that MSPs cannot sustain outer gap gamma-ray emission if the spin period is above ~ 7 ms, assuming a magnetic field of 5×10^8 G. For periods shorter than ~ 6 ms the efficiency is $\sim 4 \times 10^{-3}$ for emission above 100 MeV. Below 1.5 ms the efficiency drops rapidly with decreasing period. Based on the polar cap model, Chiang & Romaini (1993) predict that the total gamma-ray luminosity from a single MSP should scale as $L_\gamma \sim 1.5 \times 10^{33} (P_s)^{-1.4} (B_{12})^{0.95}$ ergs s^{-1}. For a magnetic field of 5×10^8 G this corresponds to a magnetospheric efficiency in the range 1×10^{-2} to 2×10^{-2} for $E > 100$ MeV.

To date, no individual MSPs have been detected at high energies. This fact by itself indicates only that a small part of the MSP spin-down power is likely converted into high-energy gamma rays. By observing globular clusters that contain large numbers of MSPs the chances of detection are strongly enhanced. The nondetections by EGRET allow upper limits to be placed on the magnetospheric efficiency η in MSPs. Since direct estimates of the spin-down power (L_{sp}) of individual MSPs in globular clusters is generally not possible because their period derivatives are not known, we take the average spin-down power of the 7 MSPs with established period derivatives as representative. Using these pulsars (PSR 1526+02A, PSR 1620−26, PSR 1639+36A, PSR 1821−24, PSR 1855+09, PSR 1937+21, PSR 1953+29), we find an average spin-down power $\langle L_{sp} \rangle \sim 2 \times 10^{35}$ ergs s^{-1}. A similar number is obtained by averaging over a population of pulsars with log B uniformly distributed between 8 and 10, which appear at a constant rate over the Hubble time of 10^{10} yr, recycled to the rebirth line $P_i \sim 1.9(B_9)^{6/7}$ ms. However there is a very large dispersion in the observed spin-down powers.

The expected gamma-ray luminosity of a cluster also depends on the number of MSPs in the cluster. Radio observations establish a lower limit in some cases, but, as noted above, model predictions range as high as several hundred in some clusters. Following Barret et al. (1993), we defined the number of potentially observable MSPs in a cluster (n_{100}) in units of 100 and the average spin-down power as $\langle L_{sp,35} \rangle$ in units of 10^{35} ergs s^{-1}. With these definitions, the EGRET upper limits on the magnetospheric conversion efficiency (η) can be derived from the limits listed in Table 2 as $\eta < 10^{-2} L_\gamma (f/4\pi)(\langle L_{sp,35} \rangle n_{100})^{-1}$, where f is the gamma-ray beaming factor that accounts for geometric beaming and the duty cycle. Note that for beamed emission, the number of potentially observable pulsars in $n(f/4\pi)$, where n is the total number of pulsars in the cluster. For 47 Tuc this gives $\eta < 3 \times 10^{-3}$. If the upper limit is based only on the observed number of MSPs, then the limit is much less stringent; i.e., for 47 Tuc $\eta < 10^{-2}$, assuming that the gamma-ray emission is beamed as the radio emission. For the other clusters in Table 2, the limits are in the range $\eta < 1.2 \times 10^{-2}$ to 8×10^{-2}. By comparison, the efficiency for young pulsars, in the same energy band ($E > 100$ MeV), ranges from $\sim 10^{-4}$ for Crab to almost unity for Gemina and PSR 1055−52 (Fierro et al. 1993). The models of MSPs mentioned above suggest η in the range 4×10^{-3} to 2×10^{-2}. Thus the EGRET observations just begin to constrain the MSP gamma-ray emission models only if one believes the globular cluster pulsar population models.

In view of the evidence of the process of ablation of a low-mass companion by radiation from a MSP, Tavani (1991) has considered a number of scenarios in which a substantial part of the energy in a relativistic $e^\pm$ wind from the pulsar can be converted into high-energy photons. In addition to the binary systems that exhibit eclipsing properties, such as PSR 1597+20 and PSR 1744−24A, Tavani argues, based on theoretical modeling of the dynamics of these systems, that a class of binaries should exist in which a MSP is completely enshrouded in material evaporated from its companion. Because the pulsar's radio emission would be absorbed in the surrounding material, these systems are referred to as "hidden" star-vaporizing pulsars (SVPs). At the interface between the pulsar wind and the enshrouding "bubble" of material, shock mechanisms operate to convert much of the energy in the wind into high-energy radiation. Depending on the wind and shock properties, the resulting photon spectrum is either a power law (photon index ~ 2) extending from a few keV to GeV energies (case I) or a spectrum peaked in the soft X-ray range (case II) (Tavani 1991). As pointed out by Barret et al. (1993), case II seems difficult to reconcile with soft X-ray observations of 47 Tuc by the *Einstein Observatory* that detected only one weak and variable soft X-ray source that is thought to be a cataclysmic variable (Hertz & Grindlay 1983). The SIGMA upper limits (40–100 keV) are also inconsistent with the prediction that hidden SVPs are bright sources of hard X-ray/soft gamma rays if 47 Tuc contains a large (≥ 20) population of such (Barret et al. 1993). We conclude that the presence of even a single gamma-ray luminous SVP in 47 Tuc is inconsistent with the EGRET upper limit of 5.3×10^{-8} photons cm^{-2} s^{-1} (95% confidence) to the photon flux above 100 MeV.

To facilitate comparison of the EGRET upper limits for other globular clusters with the flux expected from "hidden" SVPs for case I, we follow Barret et al. (1993) and write the predicted gamma-ray flux (100 MeV–30 GeV) from a single "hidden" SVP as

$$F(E > 100\ \text{MeV}) \sim 3 \times 10^{-7} \langle L_{sp,35} \rangle / d_{kpc}^2 (\epsilon/0.2) f_{\text{EGRET}} \quad \text{photons cm}^{-2}\ \text{s}^{-1} ,$$

where $\langle L_{sp,35} \rangle$ is as defined as above; d_{kpc} is the distance to the cluster in kiloparsecs; ϵ is a dimensionless parameter, normalized to the value derived from the Crab (Hoshino et al. 1992), giving the conversion efficiency of the pulsar wind into radiation; and $f_{\rm EGRET}$ is the fraction of the radiation which is in the EGRET energy band. Assuming ϵ has the value inferred for the Crab, an upper limit to the number of hidden SVPs in a cluster in $N_{\rm SVP} < (F_\gamma/3 \times 10^{-7})\langle L_{\rm sp,35}\rangle^{-1} d_{\rm kpc}^2 (f_{\rm EGRET})^{-1}$, where F_γ is the flux upper limit from Table 2. The EGRET observations are not very constraining on the presence of 1 or more hidden SVPs in these clusters assuming that the average spin-down power is 10^{35} ergs s^{-1}. However, the presence of even a single high-luminosity ($L_{\rm sp} \geq 10^{36}$ ergs s^{-1}) hidden SVP is inconsistent with the EGRET limits for about half of the clusters observed.

4. CONCLUSIONS

EGRET observations of globular clusters have not resulted in any positive detections of gamma-ray emission from the large populations of millisecond pulsars they are suspected to contain. Within the context of population models that suggest the total number of MSPs in globular clusters is $\sim 10^4$, the EGRET observations begin to constrain models of millisecond pulsar emission either due to magnetospheric emission or to reprocessing of the pulsar wind in hidden millisecond pulsars. If the total number of millisecond pulsars in globular clusters is as large as 10^5, the predicted gamma-ray fluxes from several clusters become inconsistent with the observations. Thus, with more EGRET observations in the future, establishing better upper limits or detections will be important for constraining the number of cluster pulsars as well as emission models.

The EGRET team gratefully acknowledges support from the following: Bundesministerium für Forschung und Technologie, grant 50 QV 9095 (MPE); NASA grant NAG5-1472 (HSC); NASA grant NAG5-1605 (SU); and NASA contract 5-31210 (GAC).

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