RECENTLY DISCOVERED PULSARS AND UNIDENTIFIED EGRET SOURCES

DIEGO F. TORRES, YOUSAF M. BUTT, AND FERNANDO CAMILO

1. INTRODUCTION

The Third EGRET Catalog lists 271 point sources (Hartman et al. 1999) of which about two thirds are not yet identified. Although most known young pulsars are not detected in the high-energy window (> 100 MeV), there are so far six such confirmed γ-ray pulsars (Thompson 1999). They are relatively young objects, with hard high-energy spectral indices, and apparently showing a trend for spectral hardening with increasing characteristic age (Fierro et al. 1993). Young pulsars were proposed as potential counterparts for γ-ray sources as early as 1983 (D’Amico 1983; Helfand 1994), and their relationship with unidentified EGRET sources remains a matter of current debate (see, e.g., Zhang, Zhang, & Cheng 2000).

In order to unambiguously identify a pulsar as the origin of the γ-rays from an EGRET source, γ-ray pulsations must be detected at the pulsar period. However the γ-fluxes are generally very low, and nearly contemporaneous radio/X-ray and γ-ray observations are required to fold the few available photons with the correct ephemeris. Alas this is no longer possible owing to the demise of the Compton Gamma-Ray Observatory, and new candidate associations must for now be judged by comparison with the properties of the six known EGRET pulsars.

Supernova remnants (SNRs) interacting with nearby molecular clouds have also been proposed as counterparts to many γ-ray sources (e.g. Sturmer, Dermer, & Mattox 1996; Esposito et al. 1996; Combi et al. 1998a, b, 2001), and in such cases both a pulsar and an associated interacting SNR may partially contribute to generate a given EGRET source flux.

The Parkes multibeam pulsar survey is a large-scale survey of a narrow strip of the inner Galactic plane (|b| < 5°, 260° < l < 50°; Manchester et al. 2001). It has much greater sensitivity than any previous survey to young and distant pulsars along the Galactic plane, and it has resulted in the detection of many previously unknown young pulsars, potentially counterparts of EGRET sources. In this Letter we correlate the released portion of the Parkes pulsar survey¹, now consisting of 368 pulsars, with all unidentified EGRET sources at low latitudes, in order to determine whether there are any new likely physical associations.

2. CORRELATIONS

Table 1 lists some important properties for the known EGRET γ-ray pulsars. Two of the parameters listed are highly uncertain: the distance d, and the observed efficiency for conversion of spin-down luminosity \( \dot{E} \) into γ-ray luminosity \( L_\gamma \): \( \eta \equiv \dot{E}/L_\gamma \neq f = 4\pi d^2 F_\gamma/E \), where \( F_\gamma \) is the observed γ-ray flux and \( f \) is the γ-ray beaming fraction (0 < f ≤ 1). Because this fraction is essentially unknown (see, e.g., Yadigaroglu & Romani 1995), and in part because \( f \sim 1 \) results in \( \eta \sim 100\% \) for at least one pulsar at its nominal distance, it is common practice, which we follow, to assume \( f \equiv 1/4\pi \). The efficiencies observed span the range 0.01% ≤ \( \eta \lesssim 3/19\% \): the two upper limits for \( \eta \) stem from the different measurements of the distance to PSR B1055−52 (see Ögelman & Finley 1993; Combi et al. 1997; Romero 1998). We shall then consider 0.01% ≤ \( \eta \lesssim 10\% \) as “reasonable” values for evaluating the plausibility of new associations, by analogy with presently known γ-ray pulsars, even though this inferred range relies on an assumed uniform value for \( f \), and uncertain distances.

All positional coincidences between unidentified 3EG sources and Parkes pulsars are given in Table 2. We list for each 3EG source the variability index \( I \): pulsars are steady γ-ray sources. For each pulsar we also present the “spin-down flux” \( \dot{E}/d^2 \), which is generally well-correlated with the detectability of γ-ray pulsars. A strict (linear) reading of this correlation would suggest \( L_\gamma \propto \dot{E} \), while Thompson et al. (1999) find that \( L_\gamma \propto \dot{E}^{1/2} \). However, we summarily dismiss some potential associations below owing to a low value of \( \dot{E}/d^2 \) only in extreme cases where the difference between \( \dot{E} \) and \( \dot{E}^{1/2} \)-scaling is irrelevant (and where even a hefty error in a more relevant and

¹See http://www.atnf.csiro.au/research/pulsar/pmsurv/
uncertain parameter — distance — does not change matters significantly). In all these discarded cases, in addition, the efficiencies required would be \( \eta \gg 1000\% \), making the potential associations utterly unphysical. Finally, in evaluating possible associations, we compare the photon indices of known pulsars (Table 1) with those of the EGRET sources (see, e.g., Merck et al. 1996; Zhang & Cheng 1998; Cheng & Zhang 1998).

We have also quantified the chance probability for obtaining these associations, adapting the numerical code described by Romero et al. (1999a, b): there is a 2% probability of having 8 chance coincidences between different unidentified 3EG sources and Parkes pulsars, as in Table 2.2

Camilo et al. (2001) proposed the possible physical association #1, with required efficiency of 0.5% (Table 2). This pulsar appears to be located just outside the SNR G284.3–1.8, which itself is interacting with an adjacent molecular cloud (Rui & May 1986). Another Parkes pulsar, PSR J1013–5934 (#2 in Table 2), is coincident with 3EG J1013–5915, but it is an old pulsar (\( \tau = 12 \) Myr) with \( \dot{E} = 2.5 \times 10^{32} \) ergs s\(^{-1}\) and cannot be a significant \( \gamma \)-ray contributor. D’Amico et al. (2001) have studied cases #6 and 14 (efficiencies: \( \eta = 2\% \) and 7%, respectively). Both are plausible candidates to generate the respective EGRET source fluxes. PSR J1837–0559, is also coincident with 3EG J1837–0606 (#13), but its \( \dot{E}/d^2 \) is 80 times smaller than for PSR J1837–0604, and it cannot contribute significantly to the \( \gamma \)-ray source. The pulsars in pairs #8 and 9 have far too low a spin-down luminosity at too large a distance (Table 2) to explain their coincident \( \gamma \)-ray sources. They are also both old, with \( \tau \approx 4 \) Myr. Cases #10 and 11 are discussed elsewhere in connection with a proposal for a SNR shock origin of the bulk of the \( \gamma \)-rays resulting from 3EG J1714–3857 (Butt et al. 2001); neither of these pulsars is energetic enough to contribute significant amounts of high-energy flux.

3. DISCUSSION

We now discuss the remaining four EGRET sources positionally superposed with five newly discovered pulsars. We provide observational data on the apparent associations in Tables 3 and 4. Cases #3–5, 7 and 12 all contain Vela-like pulsars, with relatively short periods, low characteristic ages, and high spin-down luminosities (\( \dot{E} \gtrsim 10^{35} \) ergs s\(^{-1}\)).

The pulsar in case #3 would require an efficiency \( \eta = 5\% \) at its nominal distance to explain the luminosity of the corresponding 3EG source, which has photon index 2.23 (see Table 4). This spectrum is softer than that of the Crab, although it is consistent with it within the uncertainties. It is also consistent with the index of 3EG 2227+6122, for which PSR J2229+6114 has been proposed as the likely source (Halpern et al. 2001). The \( \gamma \)-ray source in case #3 is not variable (Tompkins 1999; Torres et al. 2001c), as expected from direct pulsar or pulsar wind nebula/SNR shock emission. PSR J1015–5719 has \( \tau = 39 \) kyr and \( \dot{E} = 8.2 \times 10^{35} \) ergs s\(^{-1}\) (Table 3). While no cataloged SNR is superposed with the 3EG source (Torres et al. 2001b), this absence does not mean that one does not exist, and further sensitive searches may prove fruitful. Thus the connection between 3EG J1014–5705 and PSR J1015–5719 appears plausible and is worth additional study.

The pulsars in pairs #4 and 5 require unreasonably high efficiencies at their nominal distances to explain the \( \gamma \)-ray flux from the corresponding EGRET source (\( \eta \gtrsim 100\% \), Table 4). However, both pulsars are located in the direction of the Cen-taurus arm, and it is known that in such directions the electron density/distance model of Taylor & Cordes (1993) can be unreliable, sometimes overestimating the distances by factors of up to \( \sim 4 \) (see discussion in Camilo et al. 2001). Both pulsars are located (at least in projection) well within the boundaries of the incomplete shell SNR G312.4–0.4 (Caswell & Barnes 1985), to which Yadigaroglu & Romani (1997) estimate a \( \Sigma – D \) distance of 1.9 kpc. At this distance the required efficiencies for the pulsars in cases #4 and 5 would be 12% and 3%, respectively, which would make them considerably more plausible sources of the observed high energy emission. Furthermore, 3EG J1410–6147 has a photon index comparable to that of the Crab, and is not variable (Tables 1, 2 and 4). Pairs #4 and 5 therefore appear intriguing. However it should be noted that \( \Sigma – D \) distances are notoriously unreliable (e.g., for this very SNR, Caswell & Barnes 1985 and Case & Bhattacharya 1999 infer values in substantial disagreement both with each other and with that determined by Yadigaroglu & Romani 1997). Ideally, further observations of SNR G312.4–0.4 may indicate whether it shows signs of interaction with PSRs J1412–6145 or J1413–6141, and possibly constrain their distances. Depending on the actual distances, the \( \gamma \)-ray emission from 3EG J1410–6147 may conceivably arise from a combination of PSRs J1412–6145, J1413–6141, and/or SNR G312.4–0.4.

The efficiency required to explain the EGRET flux in case #7 is \( \eta = 12\% \), which seems possible. However, the spectral index of 2.50 is larger than those of known \( \gamma \)-ray pulsars. One of the SNRs coincident with the EGRET source, G337.8–0.1, harbors a maser (Koralesky et al. 1998), which is indicative of interaction between the SNR shock and the ambient medium. Thus, were a sufficiently massive molecular cloud located nearby, it could help produce the high energy radiation as a result of hadronic interaction (Aharonian, Drury, & Völk 1994; Aharonian & Atoyan 1996). Part of the EGRET flux could plausibly come from PSR J1637–4642 and part from pion \( \gamma \)-decay via SNR G337.8–0.1’s interaction with the putative cloud. In this case, the photon index would reflect a weighted average value. Both possible mechanisms for the high energy emission would produce a non-variable source, as is the case for 3EG J1639–4702.

Lastly we consider case #12, for which the required efficiency is high at the nominal pulsar distance and upper limit flux value, \( \eta = 55\% \). The pulsar is located, in projection, just outside the plerionic SNR G27.8+0.6, for which the distance is \( \sim 2 \) kpc (Reich et al. 1984). Although the estimated ages are comparable (\( \tau = 52 \) kyr for the pulsar and \( \sim 45 \) kyr for the SNR), it seems unlikely that both objects are physically associated, given the offset between the centrally peaked SNR component and the pulsar (see Reich et al. 1984). Whatever the possible relation between pulsar and SNR, the 3EG source in case #12 is variable (Table 2), arguing against a pulsar origin.

Examination of X-ray archives via HEASARC has revealed no compelling counterpart sources to any of the pulsars in Table 3. (A possible Einstein X-ray source at the edge of an IPC field near the location of PSR J1015–5719 [#3] is likely an artifact resulting from the large effective area correction used.) However, the exposures may not have been deep enough to reveal such X-ray emission, usually expected at the level \( L_x \sim 10^{-3}E \) (e.g., Becker & Trumper 1997). Future observations of these...
pulsar fields with XMM-Newton and Chandra could thus be instructive.

In conclusion, we find that two recently discovered Parkes pulsars (PSRs J1015−5719 and J1637−4642) could plausibly generate at least part of the γ-ray flux observed from two unidentified EGRET sources (3EG J1014−5703 and 3EG J1639−4702, respectively), and either of PSRs J1412−6145 or J1413−6141 could be associated with 3EG J1410−6147 if they are located closer than their DM distances by a factor of ~ 4. Cases #3–5 and 7 represent promising targets for the forthcoming AGILE and GLAST missions.

D.F.T. was supported by CONICET and Fundación Antorcha, and is on leave from IAR, Argentina. Y.M.B. acknowledges the support of the High Energy Astrophysics division at the CfA and the Chandra project. Partial support from the US DOE grant DE-FG02-91ER40671 (D.F.T.) and NASA grants NAS8-39073 (Y.M.B.) and NAG5-9095 (F.C.) is acknowledged. We thank D. Nice and G. E. Romero for comments.

REFERENCES

Aharonian, F.A., Drury, L.O’C., & Völk, H.J. 1994, A&A, 285, 645
Aharonian, F.A., & Atoyan, A.M. 1996, A&A, 309, 917
Butt, Y., Torres, D.F., Combi, J.A., Dame, T., & Romero, G.E. 2001, in preparation
Camilo, F., et al. 2001, ApJ, 557, L51
Caraveo, P.A., De Luca, A., Rignani, R.P., Rignani, G.F., 2001, (astro-ph/0107282)
Case, G., & Bhattacharya, D., 1999, ApJ 521, 246
Caswell, J.L., & Barnes, P.J. 1985, MNRAS, 216, 753
Cheng, K.S, & Zhang, L., 1998, ApJ, 498,327
Combi, J.A., Romero, G.E., & Benaglia, P. 1999, A&A, 333, L91
Combi, J.A., Romero, G.E., & Benaglia, P. 1998b, A&A, 333, L91
Combi, J.A., Romero, G.E., & Benaglia, P. 1998a, A&AS 128, 423
Combi, J.A., Romero, G.E., & Benaglia, P. 1999, ApJ, 519, L177
Combi, J.A., Romero, G.E., & Benaglia, P., & Jonas, J. 2001, A&A, 366, 1047
D’Amico, N., et al. 2001, ApJ, 552, L45
D’Amico, N. 1993, Space Sci. Rev., 63, 195
Esposito, J.A., Hunter, S.D., Kanbach, G., & Sreekumar P. 1996, ApJ, 461, 820
Fierro, J.M., et al. 1993, ApJ, 413, L27
Green, D.A. 2000, A Catalogue of Galactic Supernova Remnants, Muldowney, Radio-Astronomy, Observatory, Cambridge, UK (available at http://www.mrao.cam.ac.uk/surveys/snrs)
Haipern, J.P., Camilo, F., Gotthelf, E.V., Helfand, D.J., Kramer, M., Lyne, A.G., Leighly, K.M., & Eracleous, M. 2001, ApJ, 552, L125
Hartman, R.C., et al. 1999, ApJS, 123, 79
Helfand, D.J. 1994, MNRAS, 267, 490
Kaspi, V.M., Lackey, J.R., Mattot, J., Manchester, R.N., Bailes, M., & Pace R. 2000, ApJ, 528, 445
Koralesky, B., Frail, D.A., Goss, W.M., Clausen, M.J., & Green, A.J. 1998, AJ, 116, 1323
Manchester, R.N., et al. 2001, MNRAS, in press (astro-ph/0106522)
Mullard Radio Astronomy Observatory, Cambridge, UK (available at http://www.mrao.cam.ac.uk/surveys/snrs)
Norris, R.P., & Taylor, J.H. 1995, in International Symposium on High-Energy Gamma-Ray Astronomy, Heidelberg, Germany, in press (astro-ph/0107039)
Thompson, D.J., et al. 1999a, A&A, 357, 957
Torres, D.F., Romero, G.E., Benaglia, P., & Matsuo, T. 2001b, Proc. Int. Workshop on The Nature of Galactic Unidentified Gamma-ray Sources, O. Carramüno, O. Reimer, D. Thomson (Eds.) (Kluwer Academic Press), 97
Torres, D.F., Pessah, M.E., & Romero, G.E. 2001c, Astronomische Nachrichten (2001), in press (astro-ph/0104351)
Yadigaroglu, I-A., & Romani, R.W. 1997, ApJ, 476, 347
Zhang, L., Zhang, Y.J., & Cheng, K.S. 2000, A&A, 357, 957
Zhang, L., & Cheng, K.S. 1998, A&A, 335, 234

NOTE.—Pulsar parameters and distances (and η in the case of PSR B1951+32 — this pulsar is not a 3EG source) are taken from Kaspi et al. (2000), excepting PSR B1055−52, for which we also consider a smaller value of distance (Ogelman & Finley 1993; Combi et al. 1997), and Vela (Caraveo et al. 2001 and references therein). τ = P/2P, and E = 4π1/2P2/P, with I = 1038 g cm−2. The “P1234” γ-ray fluxes and spectral indices are from the 3EG catalog (Hartman et al. 1999), from which we have computed the η values.

### Table 1

| Pulsar/3EG Jsource | P (ms) | τ (kyr) | E (ergs s⁻¹) | d (kpc) | F₂EG [× 10⁻⁸] (ph cm⁻² s⁻¹) | γEG | η (100MeV−10GeV) |
|-------------------|-------|--------|--------------|--------|-----------------------------|------|------------------|
| Crab/0534−2200    | 33    | 1.2    | 5.0 × 10³⁸   | 2.0    | 226.2 ± 4.7                 | 2.19 ± 0.02 | 0.01% |
| Vela/0834−4511     | 89    | 12.5   | 6.3 × 10³⁶   | 0.25   | 834.3 ± 11.2                | 1.69 ± 0.01 | 0.08% |
| B1951+32/···       | 39    | 100.0  | 3.7 × 10³⁶   | 2.4    | ···                          | ···            | ···  |
| B1706−44/1710−4439 | 102   | 15.8   | 3.1 × 10³⁶   | 1.8    | 111.2 ± 6.2                 | 1.86 ± 0.04 | 1%   |
| Geminga/0633+1751  | 237   | 316.2  | 3.1 × 10³⁴   | 0.16   | 352.9 ± 5.7                 | 1.66 ± 0.01 | 3%   |
| B1055−52/1058−5234 | 197   | 501.1  | 3.1 × 10³⁴   | 0.5/1.5| 33.3 ± 3.8                  | 1.94 ± 0.10 | 2/19%|
Table 2

Positional coincidences between unidentified 3EG sources and Parkes pulsars

| 3EG J | Note | $I$ | PSR J | # | SNRs | Ref. | $\dot{E}/d^2$ |
|-------|------|-----|-------|---|------|------|--------------|
| 1013−5915 | C, em | 1.6 | 1016−5857 | 1 | G284.3−1.8 | Camilo et al. (2001) | $2.9 \times 10^{35}$ |
| 1014−5705 | C, em | 1.4 | 1015−5719 | 3 | 1412−6145 | 4 | G312.4−0.4 | $3.4 \times 10^{34}$ |
| 1410−6147 | C | 1.2 | 1413−6141 | 5 | 1413−6141 | 5 | $1.4 \times 10^{33}$ |
| 1420−6038 | C | 2.1 | 1420−6048 | 6 | D’Amico et al. (2001) | | $1.7 \times 10^{35}$ |
| 1639−4702 | C, em | 1.9 | 1637−4642 | 7 | G337.8−0.1; G338.1+0.4; G338.3+0.0 | | $1.9 \times 10^{34}$ |
| 1714−3857 | C, em | 2.1 | 1713−3844 | 10 | G348.5+0.0; G347.3−0.5 | Butt et al. (2001) | $4.0 \times 10^{31}$ |
| 1837−0423 | C | 5.4 | 1838−0453 | 12 | G27.8+0.6 | Butt et al. (2001) | $1.2 \times 10^{33}$ |
| 1837−0606 | C, em | 2.4 | 1837−0559 | 13 | 1837−0604 | 14 | D’Amico et al. (2001) | $6.5 \times 10^{32}$ |
| 1837−0604 | C, em | 2.4 | 1837−0559 | 13 | 1837−0604 | 14 | | $5.2 \times 10^{34}$ |

Note.—A number (#) is assigned to each pair for ease of reference. SNRs contained in Green’s (2000) catalog coinciding with the EGRET sources are noted (see Torres et al. 2001b). Only in cases #4, 5 and 12 do the pulsars also coincide with the SNRs listed. “C” and “em” refer to the γ-ray sources: source confusion exists and sources are possibly extended or multiple, respectively (Hartman et al. 1999). $I$ is the variability index as in Torres et al. (2001a, c), where $I > 5$ ($< 2$) represents a source whose flux presents variability levels at least 8σ (less than 2σ) above those displayed by confirmed pulsars. Pulsar “spin-down flux” $\dot{E}/d^2$ is in units of ergs s$^{-1}$ kpc$^{-2}$.

Table 3

Observational parameters for the pulsars in the candidate associations

| Case | $\Delta \theta$ [deg] | $\theta$ [deg] | $(l,b)$ | $d$ [kpc] | $\tau$ [kyr] | $P$ [ms] | $P' [10^{-15}]$ | $\dot{E}$ [ergs s$^{-1}$] |
|------|-----------------------|----------------|--------|-----------|-------------|--------|---------------|-----------------|
| #3   | 0.30                  | 0.67           | 283.09−0.58 | 4.9       | 38.7        | 140    | 57.4          | $8.2 \times 10^{35}$ |
| #4   | 0.15                  | 0.36           | 312.32−0.37 | 9.3       | 50.6        | 315    | 98.7          | $1.2 \times 10^{35}$ |
| #5   | 0.28                  | 0.36           | 312.46−0.34 | 11.0      | 13.5        | 286    | 333.4         | $5.7 \times 10^{35}$ |
| #7   | 0.46                  | 0.56           | 337.79+0.31 | 5.8       | 41.2        | 154    | 59.2          | $6.4 \times 10^{35}$ |
| #12  | 0.50                  | 0.52           | 27.07+0.71  | 8.2       | 52.2        | 381    | 115.7         | $8.3 \times 10^{34}$ |

Note.—$\Delta \theta$ is the angular distance between the center of the 3EG source and the position of the respective coincident pulsar. $\theta$ is the effective 95% confidence level radius of the 3EG source error box (Hartman et al. 1999). Pulsar parameters are taken from the Parkes survey database (see footnote 1), and their distances ($d$) are estimated from the observed dispersion measure (Taylor & Cordes 1993).
TABLE 4
OBSERVED AND COMPUTED $\gamma$-RAY EMISSION PARAMETERS FOR NEW CANDIDATE ASSOCIATIONS

| Case | $F^{3EG} \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ | $F_{3EG}^{3EG}$ [ergs cm$^{-2}$ s$^{-1}$] | $\gamma^{3EG}$ | $L_{isotropic}$ [ergs s$^{-1}$] | $L_{beamed}$ [ergs s$^{-1}$] | $\eta$ |
|------|---------------------------------|---------------------------------|-------------|-----------------|-----------------|-------|
| #3   | 34.0±6.5                        | 1.90×10$^{-10}$                 | 2.23±0.20   | 5.2×10$^{35}$   | 4.1×10$^{34}$   | 5%    |
| #4   | 64.2±8.8                        | 4.09×10$^{-10}$                 | 2.12±0.14   | 4.1×10$^{36}$   | 3.2×10$^{35}$   | 270/12%$^a$   |
| #5   | 64.2±8.8                        | 4.09×10$^{-10}$                 | 2.12±0.14   | 5.7×10$^{36}$   | 4.5×10$^{35}$   | 80/3%$^a$    |
| #7   | 53.2±8.7                        | 2.30×10$^{-10}$                 | 2.50±0.18   | 9.3×10$^{35}$   | 7.4×10$^{34}$   | 12%   |
| #12  | <19.1                           | <0.70×10$^{-10}$               | 2.71±0.44   | <5.8×10$^{35}$  | <4.6×10$^{34}$  | <55%  |

NOTE.—The EGRET fluxes correspond to the “P1234” values (Hartman et al. 1999). Luminosities, and efficiency values for all pulsars, are given for the distance estimated from the dispersion measure (Table 3).

$^a$Second values of efficiency correspond to a distance of 1.9 kpc, one of those estimated for the positionally coincident SNR G312.4–0.4 (see text).