Pulsar Searches of Unidentified \textit{EGRET} Sources

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Abstract. The majority of Galactic high-energy \(\gamma\)-ray sources continue to elude identification. Currently, we have a handful of firm pulsar identifications, one of which is radio quiet, and a few marginal detections, including one millisecond pulsar. Recently, both blind searches of \textit{EGRET} error boxes and targeted searches of X-ray counterpart candidates have had some success in finding new pulsars. I review these results, and discuss our current program of searching mid-Galactic latitude \textit{EGRET} error boxes using the Parkes multi-beam system.

1. Introduction

The \textit{EGRET} \(\gamma\)-ray telescope detected around 300 sources at energies above 100 MeV, the majority of which remain unidentified (Hartman et al. 1999). Large error boxes on the order of 1\(^\circ\) across make unambiguous identifications on the basis of source position difficult. Timing observations allow definitive identifications for sources showing aperiodic (such as active galactic nuclei) or periodic (pulsars) variability. Between 6-8 pulsars have been positively identified in the \textit{EGRET} data by epoch folding on the known period determined from radio or, in the singular case of Geminga, X-ray data (Thompson et al 1999, Kaspi et al. 2000 and references therein). Several other energetic pulsars were found to be coincident with unidentified \textit{EGRET} sources, but folding the sparse \(\gamma\)-ray data using contemporaneous radio ephemerides did not yield significant detections (Fierro, 1995). Although \textit{GLAST}, when it flies in 2006, may be able to discover new pulsars just by searching the \(\gamma\)-ray data, it is likely that a priori knowledge of a pulse period will in many cases prove crucial in determining which \(\gamma\)-ray sources are pulsars.

2. Recent Galactic Plane Pulsar Discoveries

Since the effective end of the \textit{EGRET} mission and the publishing of the third \textit{EGRET} catalog (Hartman et al. 1999), there have been both new wide scale pulsar surveys and searches of potential \(\gamma\)-ray counterparts which have yielded several new, energetic young pulsars positionally coincident with unidentified \textit{EGRET} sources. The most productive effort has been the Parkes multibeam

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survey (Manchester et al. 2001). Manchester et al. (2002) list six energetic pulsars from the PM survey which are contained within EGRET positional error boxes. For two of these, PSR J1016−5857 and PSR J1420−6048, previously obtained X-ray and radio data identified potential pulsar wind nebulae (PWN) (Camilo et al. 2001, Roberts, Romani, & Johnston 2001). Hence, searches directed at the potential counterparts would have been successful. In a third case, PSR J1015−5719, very little is known about any potential X-ray or radio PWN. In the last three cases, neither radio nor X-ray data show clear evidence for a potential source counterpart. PSR J1837−0604 is on the edge of a bright molecular cloud, making detection of a radio PWN difficult (D’Amico et al. 2001). A 10 ks Chandra image of the region shows no evidence for a X-ray point source associated with the pulsar to extremely low flux levels (Roberts et al. in preparation). The last two Parkes multibeam pulsars, PSR J1413−6141 and PSR J1412−6145, are located within the bright energetic supernova remnant G312.4−0.4. Chandra imaging and radio spectral tomography of the region show neither point sources nor potential PWN associated with either pulsar (Doherty et al. in press). The low spin-down luminosity, large distance, and alternate potential source of γ-rays (the supernova remnant) all argue against either of these latter two pulsars being the true counterpart of the coincident EGRET source.

Deep pulse searches of potential X-ray and radio counterparts have also recently proven successful. The extremely energetic pulsar PSR J2229+6114 was discovered with the Lovell telescope at Jodrell Bank in a 1.5 hr observation of a potential PWN identified by X-ray and radio imaging of the associated EGRET error box (Halpern et al. 2001). An ASCA X-ray image of the unidentified source GeV J2020+3658, associated with the COS B source 2CG 075+00, showed a point-like X-ray source at which the very small (3′) Arecibo beam could be directed. The young pulsar PSR J2021+3651, at a 20 cm flux of only 0.1 mJy, was discovered as a result (Roberts et al. 2002). This flux is about a factor of two below the sensitivity limits of the Parkes multibeam survey and similar to the sensitivity limit of a 5 hr observation with Parkes. Thus, it is possible that deep searches of potential counterparts contained within the Parkes Multibeam survey region will yield further candidates. However, three likely PWN identified by Roberts, Romani, and Kawai (2001) were searched with 5 hr pointings at Parkes and failed to yield any good candidates. Two of these, the Rabbit and GeV J1809−2327, are almost certainly PWN, based on their X-ray and radio properties (Roberts et al. 1999, Braje et al. 2002). Therefore, more sensitive radio searches might be necessary to detect the pulsars these contain. The third source, GeV J1825-1310 is less clear of a PWN candidate, due to its large size and the confused radio emission in the region, but other source classes for hard, extended X-ray sources seem less plausible.

Between the Parkes Multibeam survey and directed searches, six new strong γ-ray pulsar candidates have been discovered as radio pulsars since the demise of EGRET. Since these are young pulsars, which tend to glitch, extrapolating ephemerides back to the EGRET era is uncertain making detection of γ-ray pulsations difficult. I list these pulsars in Table 1 in boldface. The dispersion measure (DM) distances, determined using the new Cordes and Lazio (2002) NE2001 model, are given. The γ-ray efficiencies, $\eta_\gamma$, are determined from the 100 MeV to 10 GeV flux, assuming the DM distance and 1 steradian beaming.
All of the new pulsars have high DMs and have 20 cm fluxes < 1 mJy. The inferred γ-ray efficiencies are also quite high. For comparison, Table 1 lists the values for the known γ-ray pulsars, using the NE2001 distances for consistency and adapting the efficiencies from the values given by Kaspi et al. (2000). If the γ-ray sources associated with these new pulsars are nearly 100% pulsed, as are the known sources, then the oft-noted inverse correlation of efficiency with spin-down power (ηγ ∝ Lsd^−1/2, eg. Zhang & Harding 2000) and characteristic age, τc, is not well supported.

### Table 1. Radio/γ-ray? Pulsars

| Pulsar       | log \( \frac{E}{\text{erg cm}^{-2}\text{s}^{-1}} \) | log \( \tau_c \) yr | DM pc cm\(^{-3} \) | \( D_{NE2001} \) kpc | \( S_{20\text{cm}} \) mJy | \( \eta_\gamma \) |
|--------------|---------------------------------|-----------------|-----------------|---------------------|-----------------|----------|
| Crab         | 38.7                             | 3.1             | 57              | 1.7                 | 14              | 0.0001   |
| J2229+6114   | 37.3                             | 4.0             | 200             | 7.3                 | 0.3             | 0.007    |
| J1420−6048   | 37.0                             | 4.1             | 360             | 5.6                 | 0.9             | 0.01     |
| Vela         | 36.8                             | 4.1             | 68              | 0.24                | 1000            | 0.0004   |
| B1951+32     | 36.6                             | 5.0             | 45              | 3.2                 | 1.0             | 0.004    |
| B1706−44     | 36.5                             | 4.2             | 76              | 2.3                 | 10              | 0.01     |
| J2021+3651   | 36.5                             | 4.2             | 369             | 12                  | 0.1             | 0.2      |
| J1016−5857   | 36.4                             | 4.3             | 394             | 8.0                 | 0.5             | 0.03     |
| B1046−58     | 36.3                             | 4.3             | 129             | 2.7                 | 8               | 0.009    |
| J1837−0604   | 36.3                             | 4.5             | 462             | 6.4                 | 0.4             | 0.07     |
| J1015−5719   | 35.9                             | 4.6             | 283             | 5.1                 | 0.9             | 0.1      |
| B0656+14     | 34.6                             | 5.0             | 14              | 0.67                | 3.7             | 0.0007   |
| Geminga      | 34.5                             | 5.5             | -               | 0.16^a             | -               | 0.02     |
| B1055-52     | 34.5                             | 5.7             | 30              | 0.72                | -               | 0.03     |

^a. Not a radio pulsar, no DM distance available

### 3. A Mid-Latitude Survey for γ-ray Pulsars

In addition to the Galactic plane population, there is at least one distinct population of unidentified γ-ray sources at mid-Galactic latitudes. Some authors have modelled these as a Gould belt (a local region of recent star formation) population plus a Galactic Halo population (Grenier 2001). It has also been noted that the distribution is similar to that of the millisecond pulsars (Romani 2001). A population of older, Geminga-like pulsars has been postulated, as well as a population of γ-ray emitting millisecond pulsars. Indeed, there has been a recent claim of a marginal detection of pulsed γ-rays in the EGRET data set from the millisecond pulsar PSR J0218+4232 (Kuiper et al. 2000). Practically speaking, because the mid-latitude sources are generally weaker and have steeper spectra than the Galactic plane sources, they will be difficult to identify if they are not pulsed or have some other characteristic variability. If some fraction are pulsars, then a priori knowledge of the pulse period may be crucial to finding the pulsations at γ-ray energies even with the large effective area of the GLAST mission.
We have begun a survey of the unidentified mid-latitude \textit{EGRET} sources that are observable by the Parkes telescope. With the multibeam system, a series of four pointings in the standard tessellation pattern can completely cover most $\gamma$-ray error boxes out to the 95\% confidence contour. A list of 56 sources from the 3rd \textit{EGRET} catalog at latitudes $|b| > 5^\circ$ have been selected on the basis of their error box size and lack of probable AGN counterpart. Four 35 min pointings using a time resolution of 0.125 ms cover each of the error boxes. In order to be sensitive to millisecond pulsars in tight binaries, a full acceleration search will be performed using the \texttt{PRESTO} software package (Ransom 2001). The sensitivity of this survey will be similar to that of the PM survey, and much greater than the highly successful mid-latitude surveys with Parkes, which generally use only 4 min. pointings (Edwards et al. 2001).

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