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A SURVEY OF 56 MIDLATITUDE EGRET ERROR BOXES FOR RADIO PULSARS

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ABSTRACT

We have conducted a radio pulsar survey of 56 unidentified γ-ray sources from the third EGRET catalog that are at intermediate Galactic latitudes ($5^\circ < |b| < 73^\circ$). For each source, four interleaved 35 minute pointings were made with the 13 beam, 1400 MHz multibeam receiver on the Parkes 64 m radio telescope. This covered the 95% error box of each source at a limiting sensitivity of $\sim$0.2 mJy to pulsed radio emission for periods $P \gtrsim 10$ ms and dispersion measures $\lesssim$50 pc cm^{-3}. Roughly half of the unidentified γ-ray sources at $|b| > 5^\circ$ with no proposed active galactic nucleus counterpart were covered in this survey. We detected nine isolated pulsars and four recycled binary pulsars, with three from each class being new discoveries. Timing observations suggest that only one of the pulsars has a spin-down luminosity that is even marginally consistent with the inferred luminosity of its coincident EGRET source. Our results suggest that population models, which include the Gould Belt as a component, overestimate the number of isolated pulsars among the midlatitude Galactic γ-ray sources, and that it is unlikely that Gould Belt pulsars make up the majority of these sources. However, the possibility of steep pulsar radio spectra and the confusion of terrestrial radio interference with long-period pulsars ($P \gtrsim 200$ ms) having very low dispersion measures ($\lesssim$10 pc cm^{-3}, expected for sources at a distance of less than about 1 kpc) prevent us from strongly ruling out this hypothesis. Our results also do not support the hypothesis that millisecond pulsars make up the majority of these sources. Nonpulsar source classes should therefore be further investigated as possible counterparts to the unidentified EGRET sources at intermediate Galactic latitudes.

Subject headings: gamma rays: observations — pulsars: general

Online material: color figures

1. INTRODUCTION

Determining the nature of Galactic γ-ray sources with energies above 100 MeV is one of the outstanding problems in high-energy astrophysics. The Energetic Gamma-Ray Experiment Telescope (EGRET) telescope on the *Compton Gamma-Ray Observatory*, which was active from 1991 to 1999, identified about half a dozen of the brightest γ-ray sources in the Galactic plane as young pulsars (Thompson et al. 1999). It also demonstrated that most of the sources at low Galactic latitudes ($|b| \lesssim 5^\circ$) are associated with star-forming regions and hence may be pulsars, pulsar wind nebulae, supernova remnants, winds from massive stars, or high-mass X-ray binaries (Kaaret & Cottam 1996; Yadigaroglu & Romani 1997; Romero et al. 1999). In addition, molecular clouds can either be sources of γ-rays or enhance the production of γ-rays by particles produced by the source classes mentioned above (Aharonian 2001). Various targeted multiwavelength campaigns to identify low-latitude sources have discovered a number of likely counterparts (Roberts et al. 2001, 2002; Halpern et al. 2001, 2004; Braje et al. 2002). The recent Parkes Multibeam Survey has also discovered several new pulsars coincident with EGRET γ-ray sources; these pulsars have spin characteristics that are similar to those of the known γ-ray pulsars (D'Amico et al. 2001; Kramer et al. 2003).

While there are many candidate counterparts to EGRET sources at low latitudes, there are few firm identifications owing to the large positional uncertainties of the sources (typically $\sim1^\circ$ across). In general, a timing signature, such as a pulse detection, is necessary to be certain of a source identity. Since young pulsars tend to be noisy rotators, extrapolating a pulse ephemeris reliably back to the era of the EGRET observation is generally not possible. With the improved resolution and sensitivity of the upcoming *AGILE* and *Gamma-Ray Large Area Space Telescope* (*GLAST*) missions, the low-latitude EGRET sources should be more easily identified.

There are estimated to be between 50 and 100 sources detected by EGRET at mid-Galactic latitudes that are associated with our Galaxy. As a class, these sources tend to be fainter and have steeper spectra than those at low latitudes (Hartman et al. 1999). Their positional uncertainty is therefore on average even greater ($\sim1.^\circ5$ across) than it is for the low-latitude sources. These midlatitude sources have a spatial distribution that is similar to the Gould Belt of local regions of recent star formation plus a Galactic halo component (Grenier 2000, 2001). The Gould Belt provides a natural birthplace for many nearby ($\lesssim$0.5 kpc), middle-aged pulsars similar to Geminga (Halpern & Holt 1992). Both the outer gap (Yadigaroglu & Romani 1995) and polar cap (Harding & Zhang 2001) models of pulsar emission suggest that many of these pulsars should be detectable in γ-rays but that the majority should have their radio beams missing Earth. However, if predictions from recent models are realistic, then between 25% and 50% of γ-ray pulsars might still be visible to us as radio pulsars (Gonthier et al. 2004; Cheng et al. 2004).

The midlatitude EGRET source distribution is also similar to the distribution of recycled pulsars in the Galactic field (Romani 2001). The fastest millisecond pulsars (MSPs) can have spin-down luminosities ($\dot{E} \propto \dot{P}/P^3$) and magnetospheric potentials similar to those of young pulsars. There has been one possible

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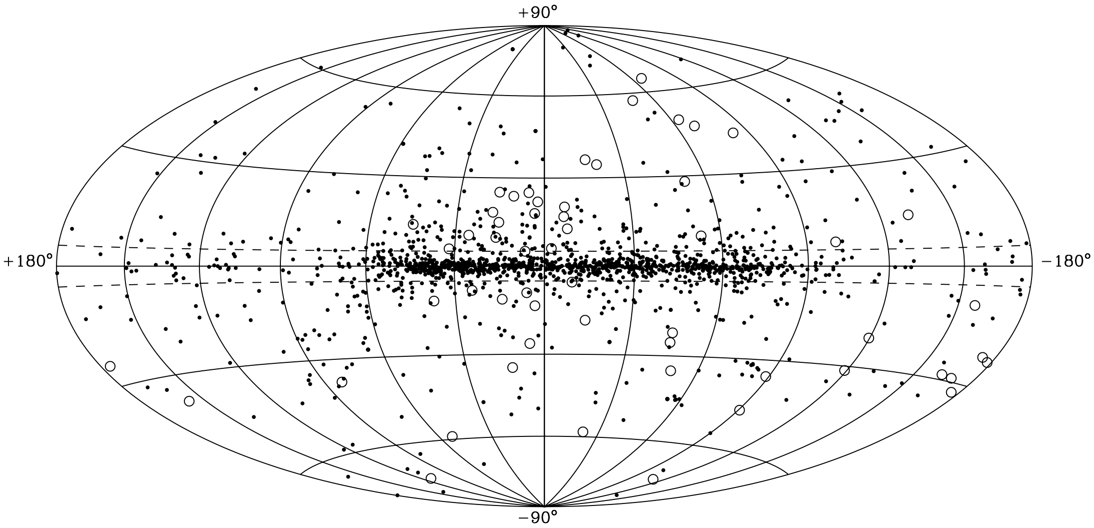

FIG. 1.—Aitoff plot in Galactic coordinates of the locations of the 56 unidentified EGRET γ-ray error boxes surveyed (*open circles*) and the known pulsars listed in the public pulsar catalog (*filled dots*) (Manchester et al. 2005). The dashed lines correspond to Galactic latitudes ±5°, the latitude limits of the Parkes Multibeam Survey (Manchester et al. 2001), which had a comparable sensitivity to the survey described here. The centers of the surveyed EGRET targets lie outside this region.

detection of γ-ray pulsations from an MSP (Kuiper et al. 2000) and some preliminary modeling of that emission (Harding et al. 2005). If a significant fraction of the midlatitude sources are MSPs at typical Galactic distances, many should be detectable as radio pulsars (Story et al. 2005). Since MSPs tend to be in binary systems, *GLAST* will not be sensitive to them in blind searches (owing to computational reasons associated with the very long integration times and the large number of trials required to search the parameter space).

Here we describe a radio pulsar survey of 56 unidentified sources from the third EGRET catalog (3EG; Hartman et al. 1999) that are at intermediate Galactic latitudes ($5^\circ < |b| < 73^\circ$). The survey used the 1400 MHz, 13 beam multibeam receiver (Staveley-Smith et al. 1996) on the 64 m radio telescope in Parkes, Australia to search for pulsed emission. This receiver has been used very successfully to find pulsars in a number of recent radio pulsar surveys (Manchester et al. 2001, 2006; Edwards et al. 2001; Kramer et al. 2003; Burgay et al. 2006). Discovery of radio pulsar counterparts to these EGRET sources would not only provide interesting systems for individual study and establish the identifications of the target sources (e.g., Roberts et al. 2002), but it would also help resolve outstanding questions about the pulsar emission mechanism and the physical origin of pulsar radiation at different wavelengths (see, e.g., Harding et al. 2004 and references therein).

2. SURVEY PARAMETERS AND DATA PROCESSING

We used four criteria in the selection of target EGRET sources for our survey. First, a source was included only if it was not in the range of the Parkes Multibeam Survey (Manchester et al. 2001), which covered Galactic latitudes $|b| < 5^\circ$. Since our targeted survey had a comparable sensitivity to the Parkes Multibeam Survey, there was no reason to repeat that coverage. Second, a source had to have no strong candidate for an active galactic nucleus (AGN) as determined by the study of Mattox et al. (2001). Third, a source had to have been easily observable by the Parkes telescope, corresponding to a declination range $\delta < +20^\circ$. Finally, the positional uncertainty from the 3EG catalog had to be sufficiently small so that a single four-pointing tessellation pattern with the multibeam receiver would cover virtually the entire 95% confidence region of the source. Using these criteria, we selected 56 unidentified EGRET γ-ray sources to survey. Figure 1 shows the sky locations of the 56 target sources and the locations of known pulsars. Table 1 lists the 56 EGRET sources with their nominal 3EG positions. These positions were used as the target centers in the first pointing of each pointing cluster. Since the beams of the multibeam receiver are spaced two beamwidths apart, four pointings are required for full coverage of a region on the sky (e.g., Manchester et al. 2001). This is illustrated in Figure 2.

We recorded a total of 3016 beams in the survey between 2002 June and 2003 July.[6] For each telescope pointing, we used a 35 minute observation sampled at 0.125 ms with 1 bit per sample; 96 contiguous frequency channels of 3 MHz each were recorded during each observation, providing a total observing bandwidth of 288 MHz centered at 1374 MHz. The observing setup was similar to the one described in detail by Manchester et al. (2001) for the Parkes Multibeam Survey, except that twice the sample rate was used here in order to increase sensitivity to MSPs. Each resulting beam contained ∼200 MB of raw data, corresponding to a total of ∼600 GB of raw survey data to be processed for pulsar signals.

The raw data from the survey were originally processed at McGill University using the Borg computer cluster and the PRESTO suite of pulsar analysis tools (Ransom 2001; Ransom et al. 2002)[7] with acceleration searches. In the search, we dedispersed each data set at 150 trial dispersion measures (DMs) ranging from 0 to 542 pc cm^{-3}, which easily encompassed the expected maximum DM for Galactic pulsars in the directions observed (Cordes & Lazio 2002; see our Table 1). The values of the DM trials were chosen such that the spacing did not add to the dispersive smearing already caused by the finite frequency channels. Since radio-frequency interference (RFI) can mask pulsar signals, we searched for RFI in particular spectral channels and time bins for each observation, and a mask was created to exclude these data from the subsequent reduction and analysis. Typically about 10%–20% of the data were rejected in this process.

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[6] Nine telescope pointings were repeated in the survey, and one pointing was missed. All other pointings were unique (see Table 1).

[7] See http://www.cv.nrao.edu/∼sransom/presto.

TABLE 1

EGRET SOURCES SURVEYED

Source Name (3EG)	95% Error Radius[a] (deg)	Right Ascension, α (J2000.0)	Declination, δ (J2000.0)	Galactic Latitude, l (deg)	Galactic Longitude, b (deg)	Maximum Expected DM[b] (pc cm^{-3})
J0038−0949[c]	0.59	00 38 57	−09 49 11	112.69	−72.44	30
J0159−3603	0.79	01 59 21	−36 03 36	248.89	−73.04	30
J0245+1758[c]	0.66[d]	02 45 26	+17 58 11	157.62	−37.11	50
J0348−5708	0.42[d]	03 48 28	−57 08 23	269.35	−46.79	40
J0404+0700[c]	0.70[d]	04 04 36	+07 00 00	184.00	−32.15	50
J0407+1710	0.71	04 07 16	+17 10 48	175.63	−25.06	70
J0426+1333	0.45[d]	04 26 40	+13 33 36	181.98	−23.82	70
J0429+0337	0.55[d]	04 29 40	+03 37 48	191.44	−29.08	60
J0439+1105	0.92	04 39 14	+11 05 24	186.14	−22.87	70
J0442−0033	0.65	04 42 11	−00 33 00	197.39	−28.68	50
J0512−6150	0.59	05 12 36	−61 50 24	271.25	−35.28	50
J0530−3626[c]	0.75	05 30 09	−36 26 23	240.94	−31.29	50
J0556+0409	0.47	05 56 14	+04 09 00	202.81	−10.29	120
J0616−3310	0.63	06 16 36	−33 10 11	240.35	−21.24	70
J0812−0646	0.72	08 12 33	−06 46 48	228.64	+14.62	90
J0903−3531	0.58	09 03 09	−35 31 47	259.40	+7.40	330
J1134−1530	0.59	11 34 38	−15 30 00	277.04	+43.48	40
J1219−1520	0.80	12 19 16	−15 20 24	291.56	+46.82	40
J1234−1318	0.76	12 34 02	−13 18 36	296.43	+49.34	40
J1235+0233	0.68[d]	12 35 14	+02 33 35	293.28	+65.13	30
J1310−0517	0.78	13 10 23	−05 18 00	311.69	+57.25	30
J1314−3431	0.56	13 14 02	−34 31 12	308.21	+28.12	70
J1316−5244	0.50[d]	13 16 57	−52 45 00	306.85	+9.93	220
J1457−1903	0.76	14 57 40	−19 03 35	339.88	+34.60	50
J1504−1537	0.70	15 04 47	−15 37 48	344.04	+36.38	50
J1616−2221	0.53[d]	16 16 07	−22 22 12	353.00	+20.03	100
J1627−2419	0.65	16 27 55	−24 19 47	353.36	+16.71	130
J1631−1018	0.72	16 31 07	−10 18 00	5.55	+24.94	80
J1634−1434	0.49[d]	16 34 07	−14 34 11	2.33	+21.78	90
J1638−2749[e]	0.62	16 38 40	−27 49 47	352.25	+12.59	190
J1646−0704	0.53[d]	16 46 28	−07 04 47	10.85	+23.69	80
J1649−1611	0.65	16 49 40	−16 12 00	3.35	+17.80	120
J1652−0223	0.73[d]	16 52 04	−02 24 00	15.99	+25.05	80
J1717−2737	0.64	17 17 12	−27 37 47	357.67	+5.95	430
J1719−0430	0.44	17 19 09	−04 30 36	17.80	+18.17	110
J1720−7820	0.75	17 20 52	−78 20 23	314.56	−22.17	90
J1726−0807	0.76	17 26 26	−08 07 11	15.52	+14.77	150
J1741−2050	0.63	17 41 38	−20 50 24	6.44	+5.00	490
J1744−3934	0.66	17 44 48	−39 34 11	350.81	−5.38	470
J1746−1001	0.76	17 46 00	−10 01 47	16.34	+9.64	250
J1800−0146	0.77	18 00 52	−01 46 47	25.49	+10.39	210
J1822+1641	0.77	18 22 16	+16 42 00	44.84	+13.84	120
J1825−7926	0.78	18 25 02	−79 26 24	314.56	−25.44	80
J1828+0142[c]	0.55	18 28 59	+01 43 12	31.90	+5.78	370
J1834−2803	0.52	18 34 21	−28 03 35	5.92	−8.97	260
J1836−4933	0.66	18 38 04	−49 33 36	345.93	−18.26	120
J1847−3219	0.80	18 47 35	−32 19 11	3.21	−13.37	180
J1858−2137	0.36[d]	18 58 26	−21 37 12	14.21	−11.15	200
J1904−1124	0.50	19 04 50	−11 24 35	24.22	−8.12	280
J1940−0121	0.79	19 40 55	−01 21 36	37.41	−11.62	170
J1949−3456	0.61	19 49 09	−34 56 23	5.25	−26.29	80
J2034−3110[c]	0.73[d]	20 34 55	−31 10 48	12.25	−34.64	60
J2219−7941	0.63[d]	22 19 59	−79 41 24	310.64	−35.06	50
J2243+1509	1.04	22 43 07	+15 10 12	82.69	−37.49	80
J2251−1341	0.77	22 51 11	−13 41 23	52.48	−58.91	30
J2255−5012	0.70[d]	22 55 57	−50 12 35	338.75	−58.12	40

NOTES.—Listed positions are the nominal 3EG positions, which were used as the target centers for the first of four interleaved pointings for each source. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Values are the radii of circles containing the same solid angle as the 95% confidence contours of the sources and were obtained from the 3EG catalog (Hartman et al. 1999).

[b] Estimated from the NE2001 Galactic electron density model (Cordes & Lazio 2002) and rounded to the nearest tens value.

[c] Identified by Sowards-Emmerd et al. (2003) or Sowards-Emmerd et al. (2004) as having a firm AGN association.

[d] Obtained by multiplying the 68% contour radius by 1.62. This is necessary in cases of unclosed or extremely irregular 95% confidence contours (Hartman et al. 1999).

[e] One of the four pointings required to cover 3EG J1638−2749 was not observed in the survey.

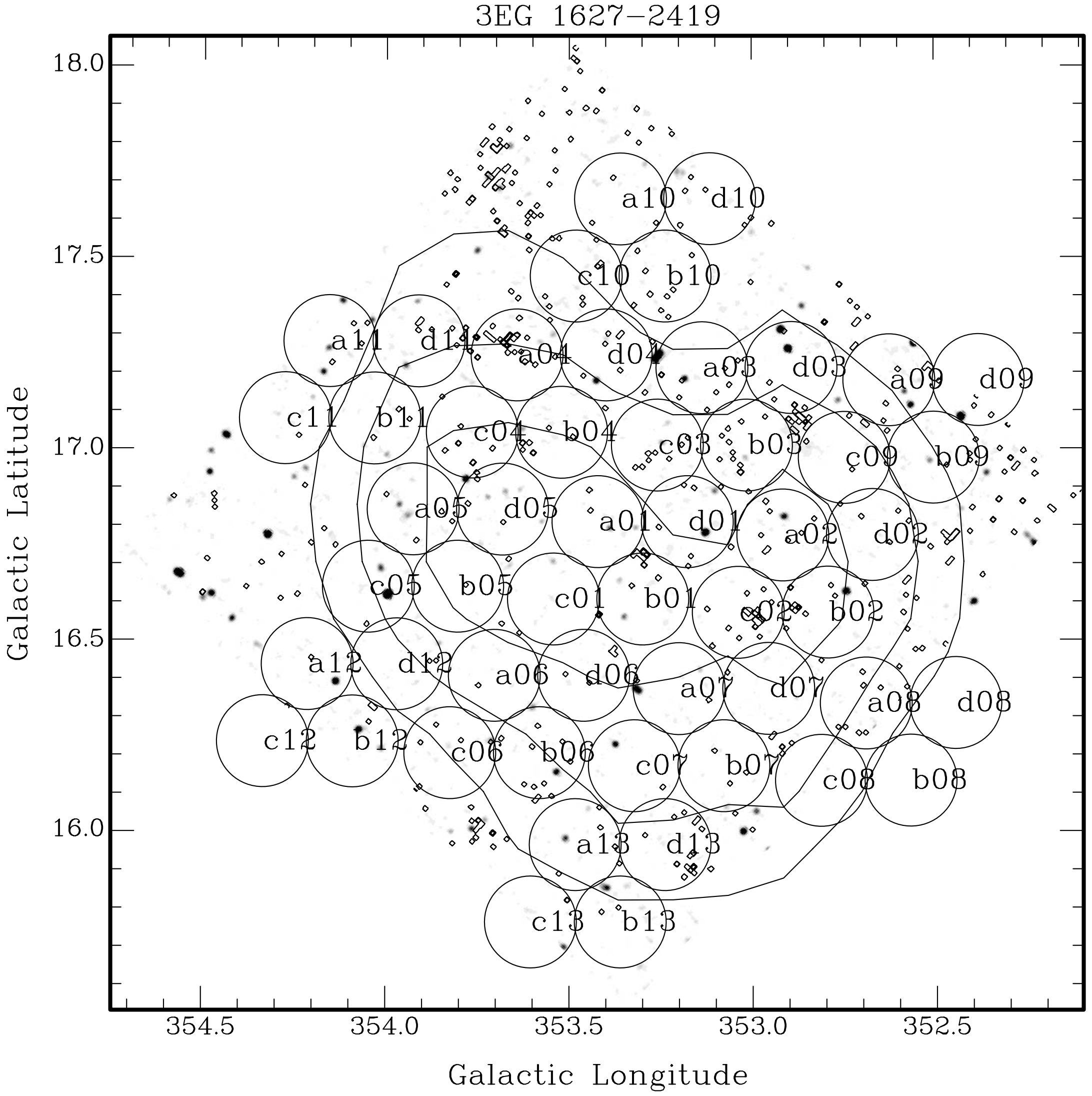

Fig. 2.—Target EGRET source 3EG J1627−2419, showing the γ-ray error box (*contour lines*), the multibeam survey coverage in our search for radio pulsations (*circles*), X-ray emission from the *ROSAT* All-Sky Survey (*pixelated squares*), and 1.4 GHz emission from the NRAO VLA Sky Survey (*gray scale*) (Condon et al. 1998). The radio and X-ray images were obtained from NASA's SkyView facility (http://skyview.gsfc.nasa.gov). The contours represent 68%, 95%, and 99% uncertainties in the γ-ray source position, and the circles indicate the Parkes half-power beam size. Four tiled multibeam pointings are shown (labeled a, b, c, and d) with 13 beams each. [*See the electronic edition of the Journal for a color version of this figure.*]

For each trial DM, we summed the frequency channels with appropriate delays to create a time series. The time series was then Fourier transformed using a fast Fourier transform (FFT), and a red noise component of the power spectrum (i.e., low-frequency noise in the data) was removed. This was done by dividing the spectral powers by the local median of the power spectrum, increasing the number of bins used in the average logarithmically with frequency. We masked known interference signals in the power spectrum, corresponding to less than 0.05% of the spectrum, and used harmonic summing with up to 8 harmonics to enhance sensitivity to highly nonsinusoidal signals. In the acceleration search, we were sensitive to signals in which the fundamental drifted linearly by up to 100 Fourier bins during the course of the observation, providing sensitivity to pulsars in tight binaries; the maximum detectable acceleration was $a_{\rm max} = 6.8P$ m s^{-2}, where P is the pulsar spin period in milliseconds. This is about 40% of the maximum acceleration searched in the Parkes Multibeam Survey processing, which used a segmented linear acceleration search (Faulkner et al. 2004; Lyne 2005). We estimate that our acceleration search would have been sensitive to all but one of the known pulsars in double neutron star binary systems (the one exception being PSR J0737−3039A). We performed folding searches around candidate periods and period derivatives and examined the results by eye. The characteristic signal of interest was a dispersed, wideband, extremely regular series of pulsations.

Averaged over the survey, the sensitivity to pulsars in an RFI-free environment was $\sim$0.2 mJy for most periods and DMs (see Fig. 3). The sensitivity calculation is outlined in Crawford (2000) and Manchester et al. (2001) and was determined for a blind FFT search. RFI tends to introduce sporadic, highly variable red noise in the power spectra, especially at low dispersion measures (DM $\lesssim 10$ pc cm^{-3}). Therefore, sensitivity to slow pulsars ($P \gtrsim 200$ ms) with low DMs is reduced in a way that is difficult to quantify. In addition, the DM peaks of long-period pulsars are broader than those of MSPs and hence are more difficult to distinguish from zero DM when the DM is very low. During this first processing run, we discovered

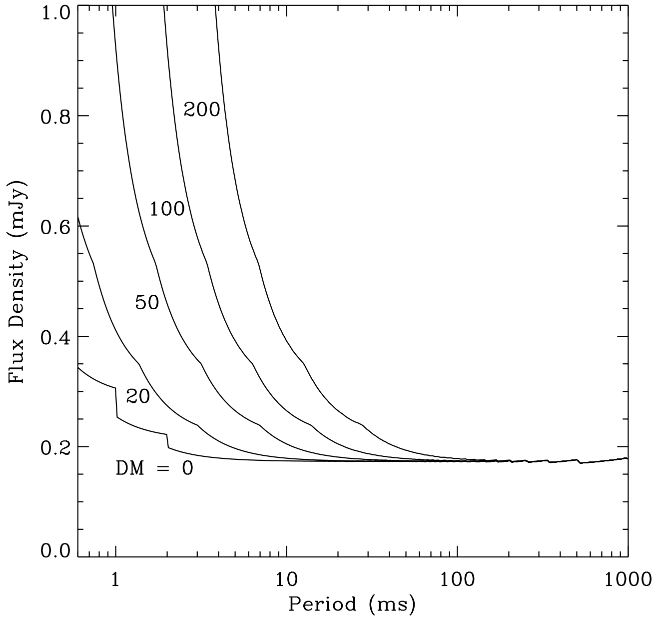

Fig. 3.—Minimum detectable 1400 MHz flux density (in the absence of RFI) as a function of pulsar period for our survey of EGRET targets. A range of DMs was assumed in the calculation, with the sensitivity curve for each DM labeled (in units of pc cm^{-3}). An intrinsic duty cycle of 5% for the pulsed emission was assumed in the sensitivity calculation as was a sky temperature of 5 K at 1400 MHz; this is the maximum sky temperature for any of our sources (Haslam et al. 1982). In the calculation, we used the gain of the center beam of the multibeam receiver, which is the most sensitive of the 13 beams. Averaging over the gains of the 13 beams of the receiver slightly increases the baseline limit to $\sim$0.2 mJy. Assuming a duty cycle smaller than 5% lowers it. The inclusion of higher order harmonics in the search is the cause of the sudden jumps in the sensitivity curves at small periods. The details of the observing system parameters and the sensitivity calculation, which is for a blind FFT search, are outlined in Crawford (2000) and Manchester et al. (2001). For the second processing run using the resampled data, the baseline limit of $\sim$0.2 mJy remains, but the sensitivity to pulsars with periods below about 20 ms is sharply degraded for all DMs (see § 2). Note that a significant red noise component in the FFT from RFI begins to degrade the sensitivity for periods $\gtrsim$200 ms and is not included in the model of the sensitivity.

six new pulsars and redetected all previously known pulsars that were within the FWHM area of the survey beams (see Table 2).

We conducted a second processing pass at Haverford College using the pulsar search packages SEEK and SIGPROC (e.g., Lorimer et al. 2000).[8] The reprocessing of the data with a different analysis package aimed to determine whether there were pulsars that were missed during the first processing pass. Of particular interest were long-period pulsars ($P \gtrsim 20$ ms), since fewer than expected were found in the first processing run. We therefore decimated the data prior to processing to reduce their size and thus significantly decrease the processing time while still maintaining sensitivity to longer period pulsars. The data were decimated by a factor of 4 in frequency and a factor of 16 in time, resulting in effective frequency channels of 12 MHz sampled every 2.0 ms. This reduced the size of each data set by a factor of 64. We were in practice sensitive to pulsars with periods greater than about 20 ms in the reprocessing of the data.

These data were dedispersed at 450 trial DMs between 0 and 700 pc cm^{-3}. The large number of DM trials ensured that no weak candidates with fast periods ($P \sim 20$–30 ms) were missed between DM steps. Each resulting time series was Fourier transformed, excised of RFI, and searched for candidate signals. We then dedispersed and folded the raw data at DMs and periods around the candidate values. We redetected all of the pulsars that had been detected in the first processing run (except for PSR J1614−2230, which has a period of $\sim$3 ms), but no additional pulsars were found. We also searched the data for dispersed single pulses. Dispersed radio bursts have recently been observed from a newly discovered class of transient radio sources; these sources are believed to be associated with rotating neutron stars (McLaughlin et al. 2006). Our single pulse search revealed no new candidates, but several known pulsars were redetected in this way. We also constructed an archive of the raw data from the survey on DVD (Cantino et al. 2004). A complete index of the survey and instructions for requesting raw data from the archive is accessible via the World Wide Web.[9]

3. RESULTS

We detected a total of 13 pulsars in the survey, six of which were new. Timing observations quickly established that three of the six new pulsars are isolated and three are in binary systems. Table 2 lists all 13 pulsars detected in the survey.

The three new isolated pulsars, PSRs J1632−1032, J1725−0732, and J1800−0125, were timed at Parkes in 2003 and 2004

TABLE 2
All Pulsars Detected in the Survey

PSR	P (s)	Dispersion Measure (pc cm^{-3})	Distance[a] (kpc)	log $\dot{E}$[b] (ergs s^{-1})	3EG Target Source	Notes
J0407+1607	0.0257	36	1.3	32.26	J0407+1710	Redetected, binary
J1614−2315	0.0335	52	1.8	31.98	J1616−2221	New, binary
J1614−2230	0.0032	35	1.3	34.09	J1616−2221	New, binary
J1632−1013	0.7176	90	>50	30.85	J1631−1018	New
J1650−1654	1.7496	43	1.4	31.38	J1649−1611	Redetected
J1725−0732	0.2399	59	1.9	33.09	J1726−0807	New
J1741−2019	3.9045	75	1.7	31.04	J1741−2050	Redetected
B1737−39	0.5122	159	3.1	32.76	J1744−3934	Redetected
J1744−3922	0.1724	148	3.1	31.11	J1744−3934	New, binary
J1800−0125	0.7832	50	1.7	32.98	J1800−0146	New
J1821+1715	1.3667	60	2.8	31.11	J1822+1641	Redetected
J1832−28	0.1993	127	3.5	31.80	J1834−2803	Redetected
J1904−1224	0.7508	118	3.3	31.84	J1904−1124	Redetected

[a] Estimated from the NE2001 Galactic electron density model of Cordes & Lazio (2002).
[b] Defined as $\dot{E} \equiv 4\pi^2 I\dot{P}/P^3$, where a moment of inertia of $I = 10^{45}$ g cm^2 is assumed.

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[8] See http://sigproc.sourceforge.net.

[9] See http://cs.haverford.edu/pulsar.

TABLE 3

Timing Parameters for Three Newly Discovered Isolated Pulsars

Name	J1632−1013	J1725−0732	J1800−0125
Right ascension, α (J2000.0)	16 32 54.20 (2)	17 25 12.281 (6)	18 00 22.08 (3)
Declination, δ (J2000.0)	−10 13 18 (1)	−07 32 59.2 (3)	−01 25 30.6 (7)
Period, P (ms)	717.63732795 (2)	239.919487227 (4)	783.18548958 (3)
Period derivative, $\dot{P}$ (10^{-15})	0.066 (1)	0.4296 (3)	11.537 (5)
Dispersion measure, DM (pc cm^{-3})	89.9 (2)	58.91 (7)	50.0 (2)
Epoch of period (MJD)	52820.00	52820.58	52820.00
rms residual (ms)	2.3	0.9	1.6
Number of TOAs	91	71	65
Timing span (days)	731	587	493
1400 MHz flux density (mJy)[a]	0.15 (5)	0.11 (3)	0.14 (4)
FWHM pulse width (% of P)	2.8	4.1	3.5
Characteristic age, τ_c (Myr)[b]	172	8.85	1.08
Surface magnetic field, B (10^{12} G)[c]	0.220	0.325	3.042
Spin-down luminosity, $\dot{E}$ (ergs s^{-1})	7.05×10^{30}	1.23×10^{33}	9.48×10^{32}

Notes.—Figures in parentheses represent the formal 1 σ uncertainties (obtained from TEMPO) in the least significant digit quoted. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Uncertainties are estimated to be ∼30% of the flux value in each case.

[b] Where $\tau_c \equiv P/2\dot{P}$.

[c] Where $B \equiv 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G.

with some supplemental observations taken with the Green Bank Telescope (GBT). We conducted timing observations at roughly monthly intervals at several central observing frequencies (mostly 1374 MHz, but also 680, 820, 1400, 1518, and 2934 MHz, depending on the receivers available at different times) and produced times of arrival (TOAs) from the observations. The observing setup was similar to the one used for timing pulsars discovered in the Parkes Multibeam Survey (Manchester et al. 2001). These data were fit to a model that included spin parameters, sky position, and DM using the TEMPO software package.[10] We used supplemental GBT observations taken in the middle of 2004 along with the original Parkes survey observations to obtain phase-connected timing solutions that spanned more than a year. Table 3 gives the full timing solutions for these three new isolated pulsars (including 1400 MHz flux densities), and Figure 4 shows their 20 cm pulse profiles.

The three new binary pulsars, PSRs J1614−2315, J1614−2230, and J1744−3922,[11] were regularly timed with Parkes and the GBT over a similar period of time (Hessels et al. 2005). These pulsars will be discussed in detail by S. Ransom et al. (2006, in preparation). We also detected a fourth binary pulsar, PSR J0407+1607, in the survey. This pulsar was previously discovered in an Arecibo drift scan survey by Lorimer et al. (2005).

If the pulsar distances estimated from the DMs using the NE2001 Galactic electron density model (Cordes & Lazio 2002) are approximately correct (to within about a factor of 2), then none of the pulsars detected has a spin-down luminosity that is large enough to clearly account for the γ-ray luminosity of its coincident EGRET source. Only the MSP PSR J1614−2230 has a spin-down luminosity of a similar magnitude to the estimated γ-ray luminosities of our sources, which, given the DM distances and EGRET fluxes, are in the 10^{34}–10^{35} ergs s^{-1} range. Even PSR J1614−2230 would have to be highly efficient to be the counterpart to its coincident γ-ray source (this will be discussed in more detail by S. Ransom et al. 2006, in preparation). Therefore, none of the pulsars is a strong candidate for an EGRET association based on its spin-down luminosity. All of the DM estimated distances to the detected pulsars ($d \gtrsim 1.3$ kpc; see Table 2) are too large to be part of a Gould Belt population, which is expected to have a distance $\lesssim 0.5$ kpc. In fact, one of the new pulsars, PSR J1632−1013, has a DM that is larger than the maximum expected DM along its line of sight. Although only about half of the surveyed EGRET sources were within 30° of the Galactic center, only PSR J1821+1715 and the long-period binary PSR J0407+1607 were detected outside this region.

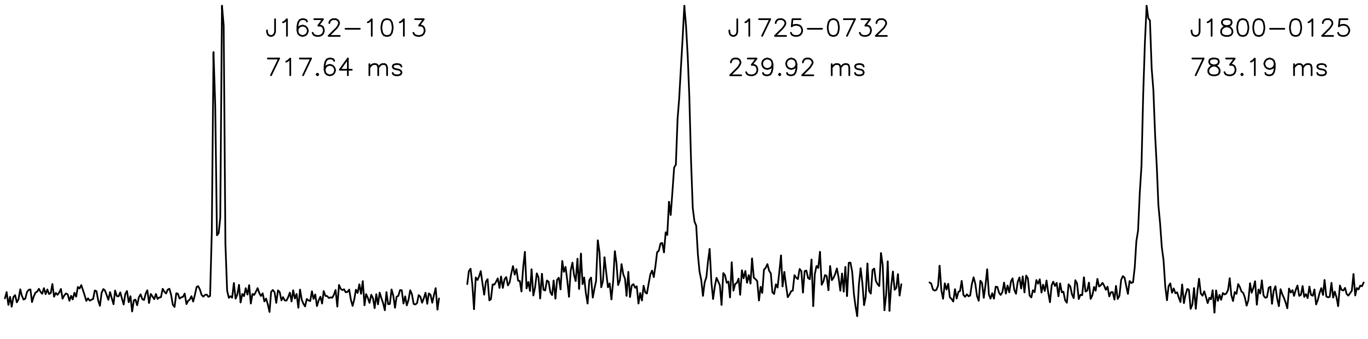

Fig. 4.—Integrated 20 cm profiles for PSRs J1632−1013, J1725−0732, and J1800−0125, the three isolated pulsars discovered in the survey. Each profile is the sum of many timing observations and has a total of 256 bins. One full period is shown in each case. Timing parameters for these pulsars, including flux densities and pulse widths, are presented in Table 3.

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[10] See http://www.atnf.csiro.au/research/pulsar/tempo.

[11] One of the new binary pulsars, PSR J1744−3922, was independently discovered in the reprocessing of the Parkes Multibeam Survey data (Faulkner et al. 2004).

4. DISCUSSION

The majority of identified EGRET sources at high Galactic latitudes are of the blazar subclass of AGNs. As stated above, we selected against these sources based on the work of Mattox et al. (2001). However, more recent radio and optical work by Sowards-Emmerd and collaborators (Sowards-Emmerd et al. 2003, 2004) on the complete sample of 3EG sources north of -40° declination has significantly expanded the number of potential AGN identifications; 33 sources remaining with no potential AGN counterparts (corresponding to roughly half of all such unidentified sources at Galactic latitudes $|b| > 5^\circ$) were included in our search. We included about one-quarter of the sources with only weak AGN candidates by their criterion as well. Six of our sources were identified in their work as having firm AGN associations (see Table 1). Therefore, for discussion purposes, we assume that 50% of all unidentified Galactic sources with $|b| > 5^\circ$ were covered in our survey.

One well-discussed model suggests that the midlatitude EGRET sources are primarily nearby, middle-aged pulsars born in the Gould Belt. This has been motivated by an apparently statistically significant spatial correlation between the unidentified γ-ray sources and the Gould Belt (Gehrels et al. 2000; Grenier 2001). Gonthier et al. (2004) have modeled the pulsar population using estimated pulsar birth rates in the Gould Belt in addition to simulating the Galactic population as a whole, and their simulations suggest that $\sim$15 pulsars ought to be detectable by EGRET at midlatitudes, roughly half of which are radio-loud (assuming a particular luminosity law and beaming model for the radio emission that is consistent with the total known population of isolated radio pulsars). However, since their simulation accounts for only $\sim$1/4 of the total unidentified γ-ray population, the hypothesis that all of the sources are pulsars would suggest that $\sim$15 radio-loud pulsars ought to have been detectable in our sample of EGRET sources. A similar study by Cheng et al. (2004), based on the outer gap emission model, finds $\sim$4 radio-loud pulsars from the Gould Belt and another four from the remainder of the Galaxy at $|b| > 5^\circ$. The total number of pulsars at midlatitudes from this simulation accounts for $\sim$1/2 the total unidentified population, indicating that our survey should have detected $\sim$8 associated radio pulsars. Both of these simulations were done using estimates of the limiting sensitivities of a variety of previous radio surveys that were mostly performed at $\sim$400 MHz and do not include the various multibeam surveys at mid- and high latitudes. Our survey covered $\sim$50% of the potential EGRET pulsars at $|b| > 5^\circ$, and yet no plausible radio candidates were discovered. The absence of detections in our survey is significant given the discrepancy between our results and the $\sim$8 and $\sim$15 detectable radio pulsars predicted in the two models under the assumption of a single source class consisting of pulsars. For a source distance of 0.5 kpc, our 1400 MHz luminosity limit was about 0.05 mJy kpc^2; the radio luminosity, L_{1400}, is defined as $L_{1400} = S_{1400}d^2$, where S_{1400} is the 1400 MHz flux density and d is the pulsar distance. This luminosity limit is lower than the 1400 MHz luminosity of all but two pulsars for which this quantity has been measured and published (Manchester et al. 2005).[12] The surveys used for the studies mentioned above were typically $\sim$4 times less sensitive than our survey (assuming an average spectral index of -2 for pulsars, as was assumed by Cheng et al. 2004). Our results suggest that the simulations significantly overestimate the radio-loud γ-ray pulsar population at midlatitudes and do not support the hypothesis that middle-aged, nearby pulsars make up the majority of the unidentified sources.

There are several important caveats to this conclusion. The first is that the average radio spectral index of middle-aged, γ-ray-emitting pulsars is unknown. If, for whatever reason, these sources preferentially have very steep radio spectra, we might not be sensitive to them at the relatively high observing frequency of this survey. The second caveat is the difficulty of distinguishing a peak at a small but nonzero DM in the data at this frequency. A clear indication of a dispersed signal is one of the important ways of distinguishing a celestial signal from local RFI. Since Gould Belt pulsars are expected to be very close to Earth ($d \lesssim 0.5$ kpc), the expected DM is less than about 10 pc cm^{-3} along many lines of sight. This often cannot be clearly differentiated from zero DM with the high observing frequency of the multibeam system. This is especially true of long-period pulsars. In fact, we detected a large number of promising candidates with pulsar-like characteristics that peaked at a DM of zero. Although we attempted (and failed) to confirm some of the most pulsar-like of these candidates at 680 MHz, we still cannot definitely rule out that some of these candidates may be astronomical sources. Observations of these sources at lower frequencies (300–400 MHz) with modern, wide-bandwidth systems (50–64 MHz) may be able to resolve these low DM and spectral index issues. However, a recent 327 MHz search of 19 midlatitude EGRET error boxes visible from the Arecibo telescope found no new pulsar counterparts (Champion et al. 2005), lending support to the conclusion that pulsars are not powering the majority of these γ-ray sources.

Although this survey detected more pulsars in binary systems per square degree (0.032 deg^{-2}) outside of globular clusters than any previous survey, PSR J1614$-$2230 was the only MSP we detected that is even a marginal counterpart candidate. Recent modeling of high-energy spectra of MSPs (Harding et al. 2005) suggests that most MSPs visible to EGRET would be active radio pulsars with significant radio luminosity. Therefore, the number of observable radio MSPs detectable by our survey should only depend on the relative radio and γ-ray beaming fractions. At large DMs (DM $\gtrsim$ 100 pc cm^{-3}), our sensitivity to MSPs is severely compromised owing to dispersive smearing. However, Table 1 indicates that less than half of our EGRET targets have a maximum expected DM greater than 100 pc cm^{-3}, and, of these, only the most distant pulsars near the edge of the Galactic electron layer would actually have such large DMs. Dispersive smearing is therefore likely not the reason why a majority of MSPs would have been missed in our survey. For a distance of $\sim$3 kpc, most of the γ-ray sources would have luminosities of $\sim 10^{35}$ ergs s^{-1}, and so we deem it unlikely that MSPs could be powering EGRET sources at distances much farther than this. At 3 kpc, our 1400 MHz luminosity limit for a 2 ms pulsar with a DM of 50 pc cm^{-3} is $\sim$5 mJy kpc^2. While the dependence of radio luminosity on spin-down luminosity is not well known for MSPs, this level of sensitivity would have allowed us to detect the majority of known MSPs. Therefore, our results do not support the hypothesis that recycled pulsars having radio luminosities similar to those of the known population make up the majority of the unidentified EGRET source population. On the other hand, the detection of a total of four binary systems in this survey indicates that deeper surveys for binary pulsars, especially within 30° of the Galactic center, appear warranted.

The detection of only three new isolated pulsars was somewhat surprising, especially since we discovered an equal number of new binary pulsars and detected six previously known isolated pulsars within the survey area (Table 2). Since our survey was $\sim$3–4 times more sensitive than previous surveys (assuming a typical spectral index), we might have expected to discover a

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[12] See http://www.atnf.csiro.au/research/pulsar/psrcat.

dozen or so new isolated pulsars. As noted above, most of the previous surveys at high latitudes were conducted at lower observing frequencies, and therefore such a simple estimate is subject to uncertainties in the spectral index and the influence of RFI. However, the strong detections of all previously known pulsars argues that these uncertainties may not be very significant.

We therefore estimate the total number of pulsars we could expect to detect at our observing frequency by comparing our results with those of the Swinburne midlatitude surveys (Edwards et al. 2001; Jacoby 2005). These surveys covered Galactic longitudes $-100^\circ < l < 50^\circ$ using the Parkes multibeam receiver and an identical observing setup to ours, but with only 1/8 the integration time. The first of these surveys covered Galactic latitudes $5^\circ < |b| < 15^\circ$ and detected 170 pulsars, including 12 binaries. By simply scaling by the area covered in this survey, the integration time, and assuming a $d \log N/d \log S$ distribution of -1 for Galactic plane pulsars at 20 cm (Bhattacharya et al. 2003), we would expect to have detected a total of $\sim$24 pulsars instead of 13. However, we should have detected only 2–3 binary pulsars, while we detected 4. The second Swinburne survey, covering $15^\circ < |b| < 30^\circ$, detected only 62 pulsars, 11 of which were binaries (Jacoby 2005). This, along with the fact that 11 of our 13 detections were within $\sim 30^\circ$ of the Galactic center, suggests a strong spatial dependence to the pulsar population out of the plane, which is hardly surprising. We therefore calculated the number of isolated pulsars we would have expected to detect within the error boxes overlapping the coverage of the Swinburne surveys given the total area covered by our survey within each Swinburne survey and within $|l| < 30^\circ$. Scaling from the surveys and assuming a $d \log N/d \log S$ distribution of -1, we should have detected $\sim$7 isolated pulsars but only $\sim$1 binary pulsar, when we actually detected 8 and 3, respectively, in this region. In the EGRET boxes within the Swinburne latitudes but outside their longitude range (presuming no further longitudinal dependence for $|l| > 30^\circ$), we would have expected $\sim$1 isolated and $\sim$0 binary pulsars, while we detected one of each. At higher latitudes, if the detection rate remained the same for $|b| > 30^\circ$ as for the second Swinburne survey ($15^\circ < |b| < 30^\circ$), we would have expected to detect $\sim$2 pulsars. No pulsars were detected in our survey at high latitudes. We therefore conclude that our results are consistent with an extrapolation from the Swinburne observations only if we take into account a strong latitudinal dependence of the isolated pulsar distribution, as expected for a disk-based population, and the apparent concentration of binary pulsars within $\sim 30^\circ$ of the Galactic center. This supports the trend in the spatial distribution of MSPs suggested by Burgay et al. (2006) obtained by combining data from the Parkes High-Latitude pulsar survey and the two Swinburne surveys. This suggests that we have not yet reached the lower luminosity limit of either the isolated or binary pulsar populations at mid-Galactic latitudes toward the Galactic center, since we found approximately what would be expected from a simple $d \log N/d \log S$ extrapolation. However, we may be reaching the luminosity limit toward the anticenter.

5. CONCLUSIONS

There are now 20 pulsars that are known to lie within 1.5 times the radius of the 95% confidence contours of EGRET sources at $|b| > 5^\circ$. Of these, only the Crab pulsar and PSR B1055−52 have confirmed associations with the coincident γ-ray emission. Of the remaining 18 pulsars, including the 13 detected in our survey and the recently discovered PSR J2243+1518 (Champion et al. 2005), none is energetic enough for a clear association. Other than PSR J1614−2230, which is at best a marginal candidate, no pulsars from any survey have been found that can be associated with unidentified EGRET error boxes at mid-Galactic latitudes. Nonpulsar source classes should therefore be investigated further. Grenier et al. (2005b) discussed the viability of low-mass microquasars as EGRET sources. Recently, it has been suggested that much of the γ-ray emission at midlatitudes is due to gas not being included in the models used for calculating the γ-ray background maps (Grenier et al. 2005a). In this case, many of the cataloged sources may not be truly pointlike. Regardless, as suggested by spectral and variability studies of the population (e.g., Grenier 2003), the likelihood of pulsars being able to account for a majority of the cataloged unidentified EGRET sources at intermediate Galactic latitudes seems remote.

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