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Pulsar searches of Fermi unassociated sources with the Effelsberg telescope

E. D. Barr,1* L. Guillemot,1* D. J. Champion,1 M. Kramer,1,2 R. P. Eatough,1 K. J. Lee,1 J. P. W. Verbiest,1 C. G. Bassa,2 F. Camilo,3,4 Ö. Çelik,5,6,7 I. Cognard,8,9 E. C. Ferrara,5 P. C. C. Freire,1 G. H. Janssen,2 S. Johnston,10 M. Keith,10 A. G. Lyne,2 P. F. Michelson,11 P. M. Saz Parkinson,12 S. M. Ransom,13 P. S. Ray,14 B. W. Stappers2 and K. S. Wood14

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
2 Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, M13 9PL
3 Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
4 Arecibo Observatory, HC3 Box 53995, Arecibo, PR 00612, USA
5 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
6 Center for Research and Exploration in Space Science and Technology (CRESST) and NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
7 Department of Physics and Center for Space Sciences and Technology, University of Maryland Baltimore County, Baltimore, MD 21250, USA
8 Laboratoire de Physique et Chimie de l’Environnement, LPCE UMR 6115 CNRS, F-45071 Orléans Cedex 02, France
9 Station de radioastronomie de Nançay, Observatoire de Paris, CNRS/INSU, F-18330 Nançay, France
10 CSIRO Astronomy and Space Science, Australia Telescope National Facility, Epping NSW 1710, Australia
11 W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
12 Santa Cruz Institute for Particle Physics, Department of Physics and Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
13 National Radio Astronomy Observatory (NRAO), Charlottesville, VA 22903, USA
14 Space Science Division, Naval Research Laboratory, Washington, DC 20375-5352, USA

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ABSTRACT

Using the 100-m Effelsberg radio telescope operating at 1.36 GHz, we have performed a targeted radio pulsar survey of 289 unassociated γ-ray sources discovered by the Large Area Telescope (LAT) aboard the Fermi satellite and published in the 1FGL catalogue (Abdo et al. 2010a). This survey resulted in the discovery of millisecond pulsar J1745+1017, which resides in a short-period binary system with a low-mass companion, $M_{c, \text{min}} \sim 0.0137 M_{\odot}$, indicative of ‘black widow’ type systems. A 2-yr timing campaign has produced a refined radio ephemeris, accurate enough to allow for phase-folding of the LAT photons, resulting in the detection of a dual-peaked γ-ray light curve, proving that PSR J1745+1017 is the source responsible for the γ-ray emission seen in 1FGL J1745.5+1018 (2FGL J1745.6+1015; Nolan et al. 2012). We find the γ-ray spectrum of PSR J1745+1017 to be well modelled by an exponentially cut-off power law with cut-off energy 3.2 GeV and photon index 1.6. The observed sources are known to contain a further 10 newly discovered pulsars which were undetected in this survey. Our radio observations of these sources are discussed and in all cases limiting flux densities are calculated. The reasons behind the seemingly low yield of discoveries are also discussed.

Key words: pulsars: general – pulsars: individual: PSR J1745+1017 – gamma-rays: general.

1 INTRODUCTION

The detection of pulsed γ-ray emission from the Crab Pulsar in the early 1970s (Vasseur et al. 1970; Grindlay 1972), the first of its kind, brought new light to the study of pulsar emission physics and high-energy emission physics in general. Gamma-ray photons

*E-mail: ebarr@mpifr-bonn.mpg.de (EDB); guillemo@mpifr-bonn.mpg.de (LG)
of energies greater than 100 keV are created in processes involving nuclear or other non-thermal reactions, and as such become important when exploring the Universe at its most energetic. The current model for the creation of $\gamma$-ray photons that we see from pulsars is that charged particles stripped from the surface are accelerated to relativistic energies in the pulsar’s strong electric field. As these particles travel along the curved magnetic field lines, they produce $\gamma$-ray photons via synchrotron radiation, curvature radiation (e.g. Ruderman & Sutherland 1975) and inverse Compton scattering from lower energy photons (e.g. Daugherty & Harding 1986). The study of these processes gives insight into the structure and composition of the magnetospheres of pulsars.

Prior to 2008, the most successful space-based $\gamma$-ray experiment was the Compton Gamma-ray Observatory (CGRO), which was in orbit for 9 yr and carried the Energetic Gamma-ray Experiment Telescope (EGRET; Kanbach et al. 1989). EGRET was sensitive to $\gamma$-ray photons in the range 20 MeV–30 GeV, and during its lifetime brought the known number of $\gamma$-ray emitting pulsars up to at least six (Thompson 2008). However, the legacy of EGRET for the radio community was not the pulsars it detected, but rather those sources for which it could make no positive association. Targeted radio searches of these 169 $\gamma$-ray sources, unassociated with either pulsars or blazars, were performed, leading to several pulsar discoveries (e.g. Champion, McLaughlin & Lorimer 2005; Keith et al. 2008).

The Large Area Telescope (LAT; Atwood et al. 2009) aboard the Fermi Gamma-ray Space Telescope, represents a significant improvement upon EGRET, providing a greater energy range and sensitivity, allowing for better measurements of source characteristics and localizations. With a host of new sources discovered, including many active galactic nuclei (AGNs) and pulsars, the Fermi-LAT is the most successful GeV $\gamma$-ray observatory to date. As with EGRET, it is those sources for which Fermi cannot immediately provide an association that have piqued the interest of the pulsar searching community. A catalogue of 1451 $\gamma$-ray sources detected above 100 MeV was created from the first 11 months of LAT data. Of these sources, 630 were unassociated with known astrophysical objects (AGNs, pulsars, etc.; Abdo et al. 2010). Multiwavelength observations of the unassociated sources were encouraged so as to determine their natures, with many radio observatories searching for radio pulsations in the Fermi observational error ellipses (e.g. Cognard et al. 2011; Keith et al. 2011; Ransom et al. 2011).

While Fermi-LAT data have already been proved to contain a wealth of pulsars, with more than 100 pulsars detected through blind periodicity searches and phase-folding of LAT photons using known pulsar ephemerides (Ray & Saz Parkinson 2011), low photon counts introduce strong selection biases in the detection of pulsars through blind searches of the LAT data. This is due to the large amount of computation required to perform wide-parameter-space searches of sparse photon data sets. For this reason, blind searches of the LAT data currently have great difficulty in detecting millisecond pulsars (MSPs) or pulsars in binary systems.

Radio pulsation searches are subject to different biases and thus are an important alternate method for identifying LAT unassociated sources as pulsars. At the time of this writing, there have been 47 radio-loud pulsars discovered through searches of these sources, of which 41 are MSPs likely to be associated with their corresponding LAT source (Ray et al. 2012). These discoveries highlight the importance of targeted radio searches of the LAT data, as these pulsars were most likely undetected in more general surveys due to shorter integration times or lack of searching for binary motion.

Of the MSPs discovered, 10 are thought to be in ‘black widow’ systems where the companion star has a very low mass due to ablation by the strong wind of the pulsar (Fruchter, Stinebring & Taylor 1988). Before Fermi only three of these systems were known to exist outside globular clusters (Fruchter et al. 1988; Stappers et al. 1996; Burgay et al. 2006), which stresses the importance of investigating this new population of pulsars uncovered by the LAT.

In this paper, we present a targeted search of 289 unassociated Fermi sources using the 100-m Effelsberg telescope operating at 1.36 GHz. The search has resulted in the discovery of a 2.65-ms pulsar, PSR J1745+1017, in a 17.5-h binary orbit with a 0.016-M\(_\odot\) companion. The positions of 10 pulsars found in other targeted searches of unassociated LAT sources are contained within the 289 sources observed. For these sources, we discuss possible reasons for our non-detections and provide flux density limits where applicable.

This paper is structured as follows. In Section 2, we discuss selection criteria for sources to be observed. In Section 3, we discuss the observational methods and data processing. In Section 4, we discuss the survey sensitivity. In Section 5, we discuss simulations of the survey. In Section 6, we discuss the results of the survey. In Section 7, we discuss the source selection and detection rate. In Section 8, we present our conclusions.

2 FERMI CATALOGUE SOURCE SELECTION

All the sources searched for this paper were selected either from the Fermi-LAT First Source catalogue (1FGL; Abdo et al. 2010a) or from an unpublished update to the 1FGL which covered the first 18 months of Fermi observations.

The 1FGL contains 630 sources unassociated with any known astrophysical object, in the 100 MeV to 100 GeV energy range. The catalogue includes source localizations defined in terms of an elliptical fit to the 95 per cent confidence level, power-law spectral fits, monthly light curves and flux measurements in five energy bands for each source. A full description of the 1FGL can be found in Abdo et al. (2010a). To narrow down the number of potentially observable sources, those below $-20^\circ$ declination, and those for which a known association existed were ignored. For all sources, the pointing position was chosen to coincide with the centre of the error ellipse. As better source localizations became available, pointing positions were altered such that they coincided with the centre of the updated error ellipse.

The remaining sources were ranked using an application of the Gaussian-mixture model as outlined in Lee et al. (2012). The best pulsar candidates exhibit significantly curved emission spectra and little $\gamma$-ray flux variability over time, in contrast with e.g. blazars and other AGNs (see e.g. fig. 17 of Nolan et al. 2012).

The top 250 ranked candidates from the 1FGL catalogue were selected to be observed. A further 39 highly ranked sources from the 18-month update to the 1FGL were also selected to be observed, giving a total of 289 target sources.

3 OBSERVATIONAL METHOD AND DATA PROCESSING

All search data presented in this paper were taken with the 100-m Effelsberg radio telescope at a centre frequency of 1.36 GHz between 2009 November and 2010 July, using the central horn of the new Effelsberg multibeam receiver with 300-MHz bandwidth.
The 289 sources selected for this survey were observed in three different observing campaigns. Initially all sources were observed with between 10- and 16-minute integrations. These integrations allowed for a preliminary shallow sweep of all sources such that the brightest pulsars, those likely to have been of the greatest use for timing applications, could be found. The second observing campaign was comprised of 32-minute integrations on 78 sources, with special focus given to covering as many of the highest ranked sources as time allowed. Finally, in the third campaign, 70 highly ranked sources were observed with between 60- and 76-minute integrations, with 32 of these sources observed multiple times. Observing in this manner reduced the effects of scintillation and of man-made radio-frequency interference (RFI), as most sources were observed multiple times with different integration times at different observing epochs.

Data were recorded over 512 filterbank channels of width 585.3 kHz with a sampling rate of 53 μs. Initially all data were sampled at 32 bits by the digitizers before being brought down to 8 bits and written to high-capacity magnetic tape for transportation and storage.

To meet the processing demands imposed by the 5.5 TB of data created in the survey, a 22-node 168-core computing cluster situated in the MPIfR was used for all data analysis. The PRESTO software package (Ransom 2001) was used for data processing.

In the first stage of the processing pipeline, data underwent RFI treatment in which a time- and frequency-dependent mask was created to be applied at a later stage. As the 1FGL catalogue contains no distance information, each beam was de-dispersed at 2760 trial dispersion measures (DMs) in the range 0–997 pc cm$^{-3}$ to mitigate against the frequency-dependent delay in the pulsar signal due to dispersion by free electrons along the line of sight. Our choice of such a fine sampling in dispersion space allows for the retention of the data’s maximum possible time resolution at all dispersion measures. The effect of this was a heightened sensitivity to millisecond and potential sub-millisecond pulsars.

All de-dispersed time series were fast-Fourier-transformed (FFT) and the resulting power spectra were de-reddened and known RFI frequencies were removed. To reconstruct power distributed through harmonics in the Fourier domain, the process of incoherent harmonic summing was used. Here the original spectra are summed and the resulting power spectra were de-reddened and known RFI and potential sub-millisecond pulsars.

In the data analysis, the theoretical minimum detectable flux density ($S_{\text{min}}$) of a pulsar can be calculated using the following equation (see e.g. Lorimer & Kramer 2005),

$$S_{\text{min}} = \beta \frac{S/N_{\text{sys}}T_{\text{sys}}}{\sqrt{N_p \delta f}} \left( \frac{P_{\text{cycle}}}{1 - P_{\text{cycle}}} \right)^{1/2},$$

where the constant factor $\beta$ denotes signal degradation due to digitization, which for 8-bit digitization is $\sim 1$ per cent, giving $\beta = 1.01$ (Kouwenhoven & Verbunt 2001). $T_{\text{sys}}$ is the system temperature of the receiver. From flux density calibration measurements we found $T_{\text{sys}} = 25$ K. $G$ is the antenna gain ($1.5$ K Jy$^{-1}$ at 1.36 GHz), $P_{\text{cycle}}$ is the pulse duty cycle, $t_{\text{obs}}$ is the length of the observation, $\delta f$ is the effective bandwidth of the receiver (240 MHz) and $N_p$ is the number of polarizations summed, which for this survey is always 2. The factor $S/N_{\text{sys}}$ is the minimum signal-to-noise ratio with which we can make a detection. Based on false alarm statistics, we chose $S/N_{\text{sys}} = 8$.

Fig. 1 shows the minimum detectable flux density as a function of spin period for four dispersion measurements: 0, 100, 500 and 1000 pc cm$^{-3}$. Assuming a pulsar of typical duty cycle 5 per cent,

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Theoretical minimum detectable flux densities ($S_{\text{min}}$) versus spin period for three integration regimes. A minimum detectable signal-to-noise ratio of 8 was imposed. The break point at period 10 ms occurs due to the assumption that the pulse duty-cycle scales as period$^{-0.5}$ with a maximum value of 1/3 (Kramer et al. 1998).}
\end{figure}
we achieve a minimum detectable flux density of 0.02 mJy for a 76-minute pointing and 0.06 mJy for a 10-minute pointing.

In a binary system, due to the Doppler effect, the apparent spin frequency of the pulsar drifts with time, spreading the pulsar’s power in the Fourier domain. To reconstruct Fourier power smeared across multiple bins, we employed the PRESTO accelsearch routine which uses the ‘correlation technique’ of template matching in the Fourier domain as outlined in Ransom, Eikenberry & Middleditch (2002). The relationship between the largest range of Fourier bins over which to search for drifted signals, \(Z_{\text{max}}\), and the acceleration to which the search is sensitive, \(a_0\), can be described by

\[
a_0 = \frac{Z_{\text{max}} P c}{t_{\text{obs}}^2},
\]

where \(P\) is the spin period of the pulsar being searched for, \(t_{\text{obs}}\) is the integration time and \(c\) is the speed of light in a vacuum.

By assuming a 1-ms period pulsar in a binary system, we may determine the sensitivity of the search at the extreme limit of the pulsar population. For the first processing pass, where the data were analysed in full length, we used \(Z_{\text{max}} = 50\) to achieve sensitivity to accelerations of up to \(|a_0| \sim 42\) and 1 m s\(^{-2}\) for 10- and 76-minute integrations, respectively. For the second processing pass, where data were analysed in 10-minute blocks, we used \(Z_{\text{max}} = 600\) to achieve sensitivity to accelerations of up to \(|a_0| \sim 500\) m s\(^{-2}\). For all systems which fall inside the acceleration limits for their integration lengths, the minimum detectable flux density may be calculated via equation (1).

5 SIMULATIONS

As with any survey that contains many pointings, we may assume that the chance detection probability for pulsars unassociated with the LAT sources targeted is non-negligible. In order to determine this probability, simulations of the normal pulsar and MSP populations were made based on the model presented in Lorimer et al. (2006) using the PSRPOP\(^2\) software. As the population distributions for MSPs and normal pulsars differ, separate simulations were performed for pulsars with rotational periods above and below 40 ms.

To simulate the normal pulsar population, input model parameters were chosen as follows.

(i) An empirical period distribution taken from the probability density function of the known population.

(ii) A log-normal luminosity distribution, with mean and variance in log space of -1.1 and 0.9, respectively (Faucher-Giguère & Kaspi 2006).

(iii) A Gaussian distribution of spectral indices, with mean of -1.6 and variance of 0.5.

(iv) An exponential distribution for the height above the Galactic plane, with a scale height of 0.33 kpc (Lorimer et al. 2006).

(v) A radial distribution as described in Lorimer et al. (2006).

(vi) The NE2001 Galactic free electron density model (Cordes & Lazio 2002).

To simulate the MSP population, the same model parameters were used with the Galactic scale height increased to 0.5 kpc to better match the known MSP distribution (Lorimer et al. 2006).

The number of pulsars simulated was such that the cumulative number of pulsars discovered in simulated versions of the Parkes Multibeam Pulsar Survey (Manchester et al. 2001), the Swinburne Intermediate-Latitude Pulsar Survey (Edwards et al. 2001) and its extension (Jacoby et al. 2009), and the Parkes High-Latitude Survey (Burgay et al. 2006), matched the real discovery numbers.

Each observation of the 289 sources in the survey was then compared against the simulated pulsar distribution to determine if a chance detection could have been made. The Galactic pulsar population was simulated 1000 times and comparisons repeated with each simulation. We find a mean detection rate of 0.4 normal pulsars and 0.04 MSPs in the 289 pointings. While not ruling out the possibility of a chance MSP detection, these figures suggest that any MSP found in this survey will be associated with the LAT source targeted at 96 per cent confidence.

6 RESULTS

6.1 PSR J1745+1017

6.1.1 Radio analysis

The main result of this work is the discovery of the radio pulsar PSR J1745+1017 in LAT source 1FGL J1745.5+1018 (2FGL J1745.6+1015). Initially discovered as a mildly accelerated candidate in a 10-minute data segment, PSR J1745+1017 has a period of 2.65 ms and a period derivative of \(2.72 \times 10^{-22}\), making it the first MSP discovered with the Effelsberg telescope.

Upon discovery, PSR J1745+1017 was the subject of an intensive timing campaign involving the Effelsberg, Lovell and Nançay radio telescopes. Pulse times of arrival (TOAs) were analysed with the TEMPO2 software package (Hobbs, Edwards & Manchester 2006) to create a phase-connected timing solution for the first 2 yr of radio observations. The pulsar ephemeris and a selection of derived properties are displayed in Table 1.

From period and period derivative measurements, we infer a characteristic age of 16.9 Gyr. Combined with the rapid spin period of PSR J1745+1017, this implies that the pulsar has undergone an extensive period of accretion-induced spin-up due to mass transfer from a companion star. This hypothesis is supported by the timing solution, which shows PSR J1745+1017 to be in a low-eccentricity binary system with an orbital period of 17.5 h and a low-mass companion. Using the definition for the binary mass function, the mass function is

\[
f(m_1, m_2) = \frac{4\pi^2 (a \sin i)^3}{G} \left( \frac{P_b}{P_0} \right)^3 = \frac{(m_1 \sin i)^3}{(m_1 + m_2)^3},
\]

where \(m_1\) and \(m_2\) are the masses of the pulsar and companion, respectively; \(G\) is Newton’s gravitational constant; \(a \sin i\) is the projected semi-major axis of the system, where \(i\) is the inclination angle of the binary (defined such that \(i = 90^\circ\) is edge on) and \(P_b\) is the orbital period, we obtain \(f(m_1, m_2) = 1.4 \times 10^{-6} \, M_\odot\). Assuming an average pulsar mass of 1.35 \(M_\odot\), this gives minimum and median companion masses of 0.014 and 0.016 \(M_\odot\), respectively.

This small range of low companion masses strongly suggests that PSR J1745+1017 is a black widow system with a white dwarf companion that has been heavily ablated by the strong particle wind from the pulsar. Unlike black widow systems such as PSR B1957+21 (Fruchter et al. 1988) and PSR J2051–0827 (Stappers et al. 1996), PSR J1745+1017 exhibits neither eclipsing behaviour nor DM variations across orbital phase, implying a low-inclination angle. If the inclination is low, then the companion mass is likely to be larger than the presented value. As noted by Lorimer & Kramer (2005), the probability of observing a binary system with an inclination less than \(i_0\) for a random distribution of orbital inclinations is \(p(i) = 1 - \cos(i_0)\). This relation suggests that the inclination angle...
is greater than 26° at 90 per cent confidence. We therefore place an upper limit of 0.032 $M_\odot$ on the mass of the companion to the same confidence level.

From proper motion measurements of PSR J1745+1017, we find a transverse velocity of $\sim 48 \pm 9$ km s$^{-1}$. The small dispersion-measure-inferred distance to this pulsar, $d \sim 1$ kpc, suggests that the Shklovskii effect (Shklovskii 1970) contribution to the measured period derivative will be non-negligible. For a pulsar with transverse velocity $v_t$, the Shklovskii effect acts to increase the intrinsic period derivative of the pulsar by a factor $v_t/c$ (see Camilo, Thorsett & Kulkarni 1994), where $c$ is the speed of light in a vacuum. We find a contribution to the period derivative of $5 \pm 2 \times 10^{-23}$ or about 18 per cent of the measured value.

Assuming a moment of inertia of $10^{45}$ g cm$^2$ and using the Shklovskii-corrected period derivative, we derive the spin-down luminosity of PSR J1745+1017 to be $E = 4\pi^2 I \dot{P}/P^3 = 4.7 \times 10^{33}$ ergs s$^{-1}$, a value which makes this pulsar a good candidate for pulsed $\gamma$-ray emission (Abdo et al. 2010a).

6.1.2 Gamma-ray analysis

In order to characterize the $\gamma$-ray emission of PSR J1745+1017, we selected Fermi-LAT data recorded between 2008 August 4 and 2012 March 7, with reconstructed energies larger than 0.1 GeV, directions within a circular region of interest (ROI) of 15° radius around the pulsar’s position, and zenith angles smaller than 100°. We further restricted the data set to ‘Source’ class events of the P7_V6 instrument response functions (IRFs), and rejected times when the rocking angle of the LAT exceeded 52° or when the Earth’s limb infringed upon the ROI. The selected $\gamma$-ray events were finally phase-folded using the ephemeris given in Table 1 and the Fermi plug-in distributed with TEMPO2 (Ray et al. 2011).

Initial pulsation searches using standard data selection cuts yielded marginal detections only. For instance, selecting photons found within 1° of the pulsar and with energies larger than 0.1 GeV, we found an $H$-test parameter (de Jager & Büsching 2010) of 15.6, which translates to a significance of $\sim 3 \sigma$. Nonetheless, pulsation searches can be made more sensitive by weighting the photons by the probability that they originate from the pulsar. These probabilities can be computed through a spectral analysis of the pulsar and the neighbouring sources (Kerr 2011; Guillemot et al. 2012).

The $\gamma$-ray spectrum of PSR J1745+1017 was measured by fitting sources in the ROI using a binned likelihood method, with the pyLikelihood module included in the Fermi Science Tools. The source model used for the analysis included the spectral parameters of the 78 sources of the Fermi-LAT Second Source Catalogue (2FGL; Nolan et al. 2012) found within 20° of the pulsar. The spectrum of PSR J1745+1017 was represented by an exponentially cut-off power-law of the form $dN/dE = N_0 (E/1 \text{ GeV})^{-\Gamma} \exp(-E/E_\gamma)$, where $N_0$ is a normalization factor, $\Gamma$ is the photon index and $E_\gamma$ is the cut-off energy. The extragalactic diffuse emission and the residual instrument background were modelled using the iso_p7v6source template, and the Galactic diffuse emission was modelled using the gal_2yearp7v6_v0 map cube. The spectral parameters of the sources within 5° of the pulsar as well as the normalizations of the diffuse models were re-fitted, while the parameters of other sources were fixed at the 2FGL catalogue values. We found no evidence of significant emission from the pulsar in the phase range [0.6; 1]. In order to increase the signal-to-noise ratio of the pulsar, we thus restricted the

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### Table 1. PSR J1745+1017 ephemeris created from TOAs taken with the Nançay, Effelsberg and Lovell telescopes over the course of 22 months.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoch of ascending node (MJD)</td>
<td>552 09.968 794 (2)</td>
</tr>
<tr>
<td>Orbital period (d)</td>
<td>0.730 241 444 (1)</td>
</tr>
<tr>
<td>Period (s)</td>
<td>0.002 652 129 671 08 (3)</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>377.055 470 138 13 (5)</td>
</tr>
<tr>
<td>Dispersion-measure-derived distance (kpc)</td>
<td>1.3(2)</td>
</tr>
<tr>
<td>Surface magnetic field (G)</td>
<td>7.7</td>
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<tr>
<td>rms residual ($\mu$)</td>
<td>5.05</td>
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### Fitted timing parameters

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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ascension (RA)</td>
<td>17:45:33.8731 (7)</td>
</tr>
<tr>
<td>Declination (Dec)</td>
<td>+10:17:52.523 (2)</td>
</tr>
<tr>
<td>Proper motion: in R.A. ($\mu_\alpha$ cos(Dec)) (mas yr$^{-1}$)</td>
<td>6 (1)</td>
</tr>
<tr>
<td>in Decl. ($\mu_\delta$) (mas yr$^{-1}$)</td>
<td>-5 (1)</td>
</tr>
<tr>
<td>Period (s)</td>
<td>0.002 652 129 671 08 (3)</td>
</tr>
<tr>
<td>Period derivative ($\times 10^{-21}$)</td>
<td>2.73 (1)</td>
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<tr>
<td>Dispersion measure (pc cm$^{-3}$)</td>
<td>23.970 (2)</td>
</tr>
<tr>
<td>Orbital period (d)</td>
<td>0.730 241 444 (1)</td>
</tr>
<tr>
<td>Epoch of ascending node (MJD)</td>
<td>552 09.968 794 (2)</td>
</tr>
<tr>
<td>$\kappa$ ($\equiv$ $\cos \omega$) ($\times 10^{-5}$)</td>
<td>0 (2)</td>
</tr>
<tr>
<td>$\eta$ ($\equiv$ $\sin \omega$) ($\times 10^{-5}$)</td>
<td>0 (2)</td>
</tr>
</tbody>
</table>

### Fixed parameters

- Reference epoch (MJD): 554 00
- Clock correction procedure: TT(TAI)
- Time system: TCB
- Solar system ephemeris model: DE414
- Binary model: ELL1 (Lange et al. 2001)

### Derived parameters

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
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<td>Frequency (Hz)</td>
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</tr>
<tr>
<td>Frequency derivative (Hz s$^{-1} \times 10^{-16}$)</td>
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<tr>
<td>Orbital eccentricity ($\times 10^{-5}$)</td>
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<tr>
<td>Epoch of periastron passage (MJD)</td>
<td>552 10.3 (4)</td>
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<tr>
<td>Mass function ($M_\odot$)</td>
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<tr>
<td>Minimum companion mass ($M_\odot$)</td>
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<tr>
<td>Median companion mass ($M_\odot$)</td>
<td>0.0158</td>
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<tr>
<td>Dispersion-measure-derived distance (kpc)</td>
<td>1.3 (2)</td>
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<tr>
<td>Characteristic age (Gyr)</td>
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<tr>
<td>Spin-down luminosity ($\times 10^{33}$ erg s$^{-1}$)</td>
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</tr>
<tr>
<td>Surface magnetic field ($\times 10^7$ G)</td>
<td>7.7</td>
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<tr>
<td>rms residual ($\mu$)</td>
<td>5.05</td>
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</table>

### Further parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median flux density at 1.63 GHz (mJy)</td>
<td>0.3</td>
</tr>
<tr>
<td>Maximum flux density at 1.36 GHz (mJy)</td>
<td>4.4</td>
</tr>
<tr>
<td>Span of timing data (MJD)</td>
<td>55 225–560 26</td>
</tr>
<tr>
<td>Number of TOAs</td>
<td>156</td>
</tr>
</tbody>
</table>

---

3 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html
data set to photons with reconstructed pulse phases between 0 and 0.6 (the \( \gamma \)-ray light curve of PSR J1745+1017, presented below, is indeed compatible with showing emission only in this phase range).

The best-fitting spectral parameters of PSR J1745+1017 are listed in Table 2, along with the integrated photon and energy fluxes above 0.1 GeV derived from these results. Systematic uncertainties were calculated by running the same analysis as described above, but using bracketing IRFs for which the effective area has been perturbed by \( \pm 10 \) per cent at 0.1 GeV, \( \pm 5 \) per cent near 0.5 GeV and \( \pm 10 \) per cent at 10 GeV, with linear interpolations in log space between.

The best-fitting spectral model for the ROI obtained from the analysis described above, we could calculate probabilities that the photons in the ROI originate from PSR J1745+1017. Selecting events found within 5° and with calculated probabilities larger than 0.01, we obtained a weighted H-test parameter (see Kerr 2011) of 58.0, corresponding to a pulsation significance of 6.5 \( \sigma \). 5 \( \sigma \) or higher is indicative of a statistically significant signal.

Fits of the two \( \gamma \)-ray peaks with Lorentzian pulse shapes above 0.3 GeV yielded the peak positions, full widths at half maxima FWHM, listed in Table 2. We also attempted to fit the light curve with one asymmetric Lorentzian pulse shape, and found that the model with two peaks is slightly preferred, at the \( \sim 4 \sigma \) level. The radio to \( \gamma \)-ray lag \( \delta = \Phi_1 - \Phi_r \) (where \( \Phi_r = 0 \) is the phase of the maximum of the radio profile shown in Fig. 2) and the \( \gamma \)-ray peaks separation \( \Delta = \Phi_2 - \Phi_1 \) are found to be \( \delta = 0.14 \pm 0.04 \) and \( \Delta = 0.26 \pm 0.06 \), respectively (see Table 2). The uncertainty on the radio to \( \gamma \)-ray lag due to the error on the measurement of the DM parameter is estimated to be \( \Delta(\delta) = \Delta(\text{DM})/(Kf_0^2) \), where \( K = 2.410 \times 10^{-4} \text{ MHz}^{-1} \text{ cm}^{-2} \text{ pe s}^{-1} \) is the dispersion constant. We find \( \Delta(\delta) \approx 10^{-3} \times P \), which is very small compared to the statistical error bar. Such values of \( \delta \) and \( \Delta \) are relatively common amongst other known \( \gamma \)-ray pulsars (see fig. 4 of Abdo et al. 2010b), and match the predictions of theoretical models that place the high-energy emission from pulsars at high altitudes in the magnetosphere (Romani & Yadigaroglu 1995).

The ephemeris used for phase-folding the \( \gamma \)-ray data considered in this analysis is based on radio timing taken after 2010 January 30 (MJD 55252). In an attempt to determine whether the ephemeris describes the rotational behaviour of the pulsar over the entire Fermi-LAT data set accurately, we analysed the evolution of the weighted H-test parameter as a function of time. The results of this analysis are shown in Fig. 3. First of all, because the H-test depends linearly on the number of photons for a given pulsed signal fraction, the linear increase of the H-test parameter as a function of the data set length provides further evidence that the pulsed \( \gamma \)-ray signal from PSR J1745+1017 is real. Moreover, the increase of the H-test parameter when going forward or backward in time is monotonic outside the formal ephemeris validity interval, which indicates that the ephemeris given in Table 1 provides a good description of the pulsar’s rotational behaviour across the entire LAT data set.

From the energy flux \( G_{100} \) measured from the spectral analysis, we calculated the \( \gamma \)-ray luminosity above 0.1 GeV using \( L_\gamma = 4\pi f_0 G_{100} \omega^2 \), where \( f_0 \) is a geometrical correction factor depending on the beaming angle of the pulsar and the viewing geometry (Watters et al. 2009). Using the distance derived from the NE2001 model of \( d = 1.3 \pm 0.2 \) kpc, we get the \( \gamma \)-ray luminosity \( L_\gamma/f_{10} \approx 1.8 \times 10^{33} \text{ erg s}^{-1} \) and the \( \gamma \)-ray efficiency, \( \eta/f_{10} \approx L_\gamma/E \approx 0.3 \). This value for the efficiency lies well within

Table 2. Measured \( \gamma \)-ray light curve and spectral parameters for PSR J1745+1017. First quoted uncertainties are statistical, and the second are systematic. Details on the determination of the systematic uncertainties are given in Section 6.1.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First peak position, ( \Phi_1 )</td>
<td>0.14 ± 0.04</td>
</tr>
<tr>
<td>First peak full width at half-maximum, FWHM(_1)</td>
<td>0.20 ± 0.16</td>
</tr>
<tr>
<td>Second peak position, ( \Phi_2 )</td>
<td>0.39 ± 0.03</td>
</tr>
<tr>
<td>Second peak full width at half-maximum, FWHM(_2)</td>
<td>0.10 ± 0.10</td>
</tr>
<tr>
<td>Radio to ( \gamma )-ray lag, ( \delta )</td>
<td>0.14 ± 0.04</td>
</tr>
<tr>
<td>( \gamma )-ray peak separation, ( \Delta )</td>
<td>0.26 ± 0.06</td>
</tr>
<tr>
<td>Photon index, ( \Gamma )</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>Cut-off energy, ( E_c ) (GeV)</td>
<td>3.2 ± 1.2</td>
</tr>
<tr>
<td>Photon flux (&gt;0.1 GeV), ( F_{100} ) (10(^{-8}) cm(^{-2}) s(^{-1}))</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>Energy flux (&gt;0.1 GeV), ( G_{100} ) (10(^{-12}) erg cm(^{-2}) s(^{-1}))</td>
<td>9.3 ± 1.3</td>
</tr>
<tr>
<td>Luminosity, ( L_{\gamma}/f_{10} ) (10(^{33}) erg s(^{-1}))</td>
<td>1.8 ± 0.6</td>
</tr>
<tr>
<td>Efficiency, ( \eta/f_{10} )</td>
<td>0.3 ± 0.1</td>
</tr>
</tbody>
</table>
This value is half that of the published flux density at 1.5 GHz, (1), we found a corresponding estimated flux density of 0.08 mJy. The pulsar lies below the detection threshold of this survey. Using equation a detection of the pulsar at signal-to-noise ratio 6.4, a value which is consistent with the observations. We note here that this pulsar was discovered using the pulsar timing array. It should be noted that this pulsar was discovered using the Robert C. Byrd Green Bank Telescope in the US, where the mains frequency is 60 Hz. The mains are often lost in noise or excised from the data in the process of Fourier RFI excision, wherein known RFI signals are removed from the power spectrum of the observation prior to pulse detection. A discrepancy which may be attributed to the extra noise induced by the oscillations of the mains electricity at the folding period. It should be noted, that the derived position of J2030+3641 is coincident with the position observed in this survey.

6.2 Radio pulsar non-detections

During the course of the observations, other observatories discovered six radio-emitting pulsars associated with the sources observed in this survey. These pulsars were not detected in this survey due to a combination of reasons, such as limited flux density, local RFI conditions and source position redefinitions. Further information on all sources observed in this work may be found in the corresponding online material, with the 15 highest ranked sources presented in Table A1.

6.2.1 PSR J2030+3641

PSR J2030+3641 (Camilo et al. 2012), initially undetected in our data processing, exhibits a rotational frequency which is similar to the 10th sub-harmonic of the 50-Hz local mains frequency. Unfortunately signals which are similar in frequency to harmonics of the mains are often lost in noise or excised from the data in the process of Fourier RFI excision, wherein known RFI signals are removed from the power spectrum of the observation prior to pulse detection. It should be noted that this pulsar was discovered using the Robert C. Byrd Green Bank Telescope in the US, where the mains frequency is 60 Hz.

Reprocessing of these data with the published ephemeris yielded a detection of the pulsar at signal-to-noise ratio 6.4, a value which lies below the detection threshold of this survey. Using equation (1), we found a corresponding estimated flux density of 0.08 mJy. This value is half that of the published flux density at 1.5 GHz, a discrepancy which may be attributed to the extra noise induced by the oscillations of the mains electricity at the folding period. It should be noted, that the derived position of J2030+3641 is coincident with the position observed in this survey.

6.2.2 PSRs J1646−2142, J1816+4510 and J1858−2218

PSRs J1646−2142, J1858−2218 (Ray et al. 2012) and J1816+4510 (Kaplan et al. 2012) were all discovered at LAT positions that were significantly different from the position determined in the 1FGL catalogue. Because of this, the discovery position of these pulsars is a half-beamwidth or more away from the position observed in this work, and so no detection is expected.

6.2.3 PSRs J0307+7443 and J1828+0625

PSRs J0307+7443 and J1828+0625 (Ray et al. 2012) were both discovered at positions coincident with sources observed in this survey. Both pulsars were detected at low radio frequency and appear to be weak radio emitters. Assuming similar profile characteristics at both 1.36 GHz and at the discovery frequency, we found upper limits of 0.1 and 0.2 mJy on the radio flux densities at 1.36 GHz for PSRs J0307+7443 and J1828+0625, respectively.

6.3 Gamma-ray pulsar non-detections

Through blind searches of Fermi-LAT photons, a further four pulsars associated with the sources observed have since been discovered (Saz Parkinson et al. 2012). No radio detection has so far been made for these pulsars, therefore in Table 3 we present our upper limits on their radio flux densities at 1.36 GHz.

A simple model for the telescope beam was used to adjust limiting flux densities for position offsets between the pointing and true position of the source. Limiting flux densities were divided by a factor q, given by $q = e^{-q_0 \theta^2/2}$, where $\theta_0$ is the pointing offset and $\theta$ is the beam half-width at half-maximum, to return the true limiting flux density at 1.36 GHz ($S_{\text{lim}}$).

7 DISCUSSION

Considering the success that other surveys of unassociated Fermi-LAT sources have had (Cognard et al. 2011; Keith et al. 2011; Ransom et al. 2011; Camilo et al. 2012), we must consider the reasons behind our relatively small yield of discoveries. Sources observed in this work were selected based on information provided in the 1FGL catalogue. However, in the recently published 2FGL catalogue, many of these sources are no longer listed. A detailed description of the possible causes for this can be found in Table A1.

<table>
<thead>
<tr>
<th>PSR</th>
<th>Pointing offset (°)</th>
<th>$S_{\text{lim}}$ (mJy)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0734−1559</td>
<td>0.05</td>
<td>0.1</td>
<td>Saz Parkinson (2011)</td>
</tr>
<tr>
<td>J1803−2149</td>
<td>0.05</td>
<td>0.1</td>
<td>Pletsch et al. (2012)</td>
</tr>
<tr>
<td>J2030+4415</td>
<td>0.02</td>
<td>0.08</td>
<td>Pletsch et al. (2012)</td>
</tr>
<tr>
<td>J2139+4716</td>
<td>0.04</td>
<td>0.09</td>
<td>Pletsch et al. (2012)</td>
</tr>
</tbody>
</table>

Reprocessing of these data with the published ephemeris yielded a detection of the pulsar at signal-to-noise ratio 6.4, a value which lies below the detection threshold of this survey. Using equation (1), we found a corresponding estimated flux density of 0.08 mJy. The pulsar lies below the detection threshold of this survey. Using equation a detection of the pulsar at signal-to-noise ratio 6.4, a value which is consistent with the observations. We note here that this pulsar was discovered using the pulsar timing array. It should be noted, that the derived position of J2030+3641 is coincident with the position observed in this survey.
section 4.2 of Nolan et al. (2012). Using the 2FGL catalogue to examine the 289 sources selected for observation, we find:

(i) 106 sources that are no longer listed;
(ii) 46 sources that have moved by more than half the FWHM of the telescope beam;
(iii) 22 sources marked as potentially spurious.

Selecting against these sources and choosing only sources for which the entire updated 95 per cent confidence region was contained within the FWHM of the telescope beam, we are left with 72 sources for which observations adequately cover the LAT source targeted.

This would suggest that the detection rate for the survey is ~1.4 per cent. However, as noted by Camilo et al. (2012), a large number of pulsar surveys at radio wavelengths have focused on observing the Galactic plane at low latitudes, introducing a strong bias against the discovery of new radio-emitting pulsars in this volume. Selecting only those 58 sources that lie in the region |b| > 3.5, we find the detection rate to be 1.7 per cent.

We note that the strategy employed by other surveys of LAT unassociated sources has generally been to select a small number of sources and observe with long integration times, often at lower frequencies (e.g. Ransom et al. 2011). By contrast, we have selected a large number of sources and observed at various integration lengths at higher frequency. Although this strategy has lacked the discoveries that other searches have made, it has provided the most complete picture yet of the LAT sky at high radio frequencies.

The results of our survey suggest that future surveys of unassociated LAT sources would benefit from lower observing frequencies, as wider beam-widths will increase the LAT error ellipse area, which, when combined with the decrease in LAT error ellipse size due to increasing observation depth, will significantly reduce the problems associated with source redefinitions. Furthermore, we note that the majority of pulsars discovered through radio searches of the LAT data have been found at low frequencies. This suggests that this population of pulsars may have particularly steep spectral indices. Continued multifrequency study of pulsars discovered in unassociated LAT sources will deny or confirm this hypothesis.

8 CONCLUSION

We have performed repeated observations of 289 unassociated sources from the First Fermi-LAT catalogue of γ-ray sources, resulting in the discovery of PSR J1745+1017.

PSR J1745+1017 has a 2.65-ms spin period and orbits a very low mass companion with an orbital period of 17.5 h. The low mass of the companion suggests that PSR J1745+1017 is a black widow system; however, a two-year timing campaign has thus far found no evidence of eclipses, dispersion measure variations across orbital phase or Shapiro delay. By performing weighted-probability analysis of LAT photons in the ROI around PSR J1745+1017, we also detected γ-ray pulsations from the source. This gives a clear indication that PSR J1745+1017 is responsible for the γ-ray emission seen from 2FGL J1745.5+1018 (2FGL J1745.6+1015).

The observed sample contains three radio pulsars, newly discovered through similar searches performed by other observatories, and four γ-ray-selected, radio-quiet pulsars, found through blind searches of Fermi-LAT data.

No radio detection was made for the four γ-ray-selected pulsars contained in our sample. The upper limits on their radio flux densities at 1.36 GHz were calculated. These limits can be found in Table 3.

Of the three newly discovered radio pulsars coincident with LAT sources searched in this survey, only PSR J2030+3641 was detected using the known timing solution. PSRs J0307+7443 and J1828+0625 were suspected to have radio flux densities at 1.36 GHz lower than the limiting flux density of our observations.

ACKNOWLEDGMENTS

This work was carried out based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg.

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We would like to thank Matthew Kerr for his input regarding initial source selection. Pulsar research and observations at Jodrell Bank Observatory have been supported through rolling grants from the UK Science and Technology Facilities Council (STFC).

REFERENCES

Abdo A. A. et al., 2010a, ApJS, 188, 405
APPENDIX A: SAMPLE POINTING INFORMATION

Table A1. Sample of observed sources as ranked by the 2FGL logarithmic likelihood, 2FGL $R_{95}$, found through application of Gaussian-mixture modelling (Lee et al. 2012) to the 2FGL catalogue. $R_{95}$ values are the major axes of the 95 per cent error ellipses for each source as found in the 1FGL and 2FGL catalogues. Limiting flux densities are calculated by the method outlined in Section 4, with a 10 per cent duty cycle imposed. Both Galactic coordinates, $l$ and $b$, and equatorial coordinates, RA and Dec., show the true pointing position of each observation. A complete table of all sources observed can be found in electronic form online.

<table>
<thead>
<tr>
<th>Index</th>
<th>1FGL name</th>
<th>2FGL name</th>
<th>$l$</th>
<th>$b$</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>Offset from 2FGL ($\circ$)</th>
<th>1FGL $R_{95}$ ($\circ$)</th>
<th>2FGL $R_{95}$ ($\circ$)</th>
<th>Observations (minutes)</th>
<th>Limiting flux density (mJy)</th>
<th>1FGL $R_{1289}$</th>
<th>2FGL $R_{1289}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>J1906.5+0716c</td>
<td>J1906.5+0720</td>
<td>41.13</td>
<td>-0.02</td>
<td>19:06:36</td>
<td>19:06:36</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
<td>32</td>
<td>0.10</td>
<td>11.9</td>
<td>18.2</td>
</tr>
<tr>
<td>2</td>
<td>J1819.3--1518c</td>
<td>J1819.3--1523</td>
<td>15.70</td>
<td>-0.05</td>
<td>18:19:25</td>
<td>18:19:25</td>
<td>0.09</td>
<td>0.12</td>
<td>0.12</td>
<td>36</td>
<td>0.09</td>
<td>7.27</td>
<td>15.5</td>
</tr>
<tr>
<td>3</td>
<td>J1932.1+1914c</td>
<td>J1932.1+1913</td>
<td>54.61</td>
<td>0.10</td>
<td>19:32:10</td>
<td>19:32:10</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>32</td>
<td>0.10</td>
<td>7.57</td>
<td>13.8</td>
</tr>
<tr>
<td>4</td>
<td>J1946.8--0233c</td>
<td>J1947.2--0236</td>
<td>30.12</td>
<td>-0.14</td>
<td>18:46:48</td>
<td>18:46:48</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
<td>32</td>
<td>0.10</td>
<td>6.85</td>
<td>13.4</td>
</tr>
<tr>
<td>5</td>
<td>J1625.9--0019</td>
<td>J1625.9--0020</td>
<td>13.95</td>
<td>31.81</td>
<td>16:25:20</td>
<td>16:25:20</td>
<td>0.03</td>
<td>0.08</td>
<td>0.06</td>
<td>32</td>
<td>0.10</td>
<td>4.36</td>
<td>12.2</td>
</tr>
<tr>
<td>6</td>
<td>J0224.0+6201c</td>
<td>J0224.0+6204</td>
<td>133.56</td>
<td>1.07</td>
<td>02:24:02</td>
<td>02:24:02</td>
<td>0.06</td>
<td>0.07</td>
<td>0.06</td>
<td>32</td>
<td>0.10</td>
<td>11.9</td>
<td>12.2</td>
</tr>
<tr>
<td>7</td>
<td>J0200.9+4411</td>
<td>J0200.7+4417</td>
<td>82.30</td>
<td>2.84</td>
<td>20:30:55</td>
<td>20:30:55</td>
<td>0.10</td>
<td>0.09</td>
<td>0.07</td>
<td>10</td>
<td>0.18</td>
<td>8.21</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>J1857.9+0352c</td>
<td>J1857.8+0355c</td>
<td>37.13</td>
<td>0.31</td>
<td>18:58:00</td>
<td>18:57:00</td>
<td>0.05</td>
<td>0.07</td>
<td>0.16</td>
<td>32</td>
<td>0.10</td>
<td>12.7</td>
<td>11.9</td>
</tr>
<tr>
<td>9</td>
<td>J2030.0+3641</td>
<td>J2030.0+3640</td>
<td>76.12</td>
<td>-1.44</td>
<td>20:30:00</td>
<td>20:30:00</td>
<td>0.01</td>
<td>0.06</td>
<td>0.04</td>
<td>10</td>
<td>0.18</td>
<td>9.82</td>
<td>11.8</td>
</tr>
<tr>
<td>10</td>
<td>J0308.6+7442</td>
<td>J0308.3+7442</td>
<td>131.75</td>
<td>14.24</td>
<td>03:08:37</td>
<td>03:08:37</td>
<td>0.07</td>
<td>0.10</td>
<td>0.06</td>
<td>32</td>
<td>0.10</td>
<td>3.57</td>
<td>11.7</td>
</tr>
<tr>
<td>11</td>
<td>J0608.3+2038c</td>
<td>J0608.3+2037</td>
<td>189.76</td>
<td>0.29</td>
<td>06:08:20</td>
<td>06:08:20</td>
<td>0.00</td>
<td>0.09</td>
<td>0.11</td>
<td>32</td>
<td>0.10</td>
<td>4.4</td>
<td>9.89</td>
</tr>
<tr>
<td>12</td>
<td>J0322.8+3928</td>
<td>J0336.3+3927</td>
<td>78.69</td>
<td>-0.24</td>
<td>20:32:48</td>
<td>20:32:48</td>
<td>0.21</td>
<td>0.25</td>
<td>0.12</td>
<td>32</td>
<td>0.10</td>
<td>1.65</td>
<td>9.68</td>
</tr>
<tr>
<td>13</td>
<td>J0426.5+5437</td>
<td>J0426.7+5434</td>
<td>150.84</td>
<td>3.87</td>
<td>04:26:35</td>
<td>04:26:35</td>
<td>0.06</td>
<td>0.14</td>
<td>0.11</td>
<td>32</td>
<td>0.10</td>
<td>2.99</td>
<td>9.38</td>
</tr>
</tbody>
</table>
SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Observed sources as ranked by the 2FGL logarithmic likelihood, 2FGL $R_95$, found through application of Gaussian-mixture modelling (Lee et al. 2012) to the 2FGL catalogue. R95 values are the major axes of the 95 per cent error ellipses for each source as found in the 1FGL and 2FGL catalogues. Limiting flux densities are calculated by the method outlined in Section 4, with a 10 per cent duty cycle imposed. Both Galactic coordinates, $l$ and $b$, and equatorial coordinates, RA and Dec., show the true pointing position of each observation (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/sts449/-/DC1).

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