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TWO YOUNG RADIO PULSARS COINCIDENT WITH EGRET SOURCES

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ABSTRACT

We report the discovery and follow-up timing observations of two young energetic radio pulsars. PSR J1420−6048 has a period $P = 68$ ms and period derivative $\dot{P} = 83 \times 10^{-15}$, implying a characteristic age $\tau_c = 13$ kyr and a surface dipole magnetic field strength $B = 2.4 \times 10^{12}$ G. PSR J1837−0604 has $P = 96$ ms and $\dot{P} = 45 \times 10^{-15}$, implying $\tau_c = 34$ kyr and $B = 2.1 \times 10^{12}$ G. The two objects have large spin-down luminosities, and, on the basis of an empirical comparison of their properties with those of other young radio pulsars, they are expected to be observable as pulsed γ-ray sources. In fact, they lie within the error circles of γ-ray sources detected by the EGRET instrument on the *Gamma Ray Observatory*. We show that the pulsars are plausibly associated with the EGRET sources.

Subject headings: pulsars: general — pulsars: individual (PSR J1420−6048, PSR J1837−0604) — stars: neutron

1. INTRODUCTION

The Parkes multibeam pulsar survey is a large-scale survey of a 10° wide strip along the Galactic plane between Galactic longitudes of −100° and +50°. This survey uses the Parkes 64 m radio telescope at the relatively high radio frequency of 1.4 GHz, thereby reducing the effects of interstellar dispersion and scattering and of Galactic background radiation. It has a much higher sensitivity than any previous similar survey and hence is finding large numbers of previously unknown pulsars, many of which are relatively young and distant (e.g., Lyne et al. 2000; Camilo et al. 2000; D'Amico et al. 2000; Manchester et al. 2000).

Because of their rapid evolution, young pulsars are relatively rare in the known pulsar population. However, they are particularly interesting objects for many reasons: they are likely to be associated with supernova remnants (e.g., Kaspi 2000), they generally exhibit rotational instabilities including glitches (e.g., Arzoumanian et al. 1994; Wang et al. 2000), and they sometimes emit detectable pulsed radiation at optical (e.g., Middleditch, Pennypacker, & Burns 1987), X-ray (e.g., Becker & Trümper 1997), and γ-ray (e.g., Thompson et al. 1999) frequencies. Young pulsars have been proposed as potential counterparts of the unidentified high-energy γ-ray sources (D'Amico 1983; Helfand 1994), but searches for associated pulsars in the direction of γ-ray sources have not been productive (e.g., Manchester, D'Amico, & Tuohy 1985).

There is a very strong correlation of high-energy detectability with the spin-down energy flux $\dot{E}d^{-2}$, where $\dot{E} = 4\pi^2 I\dot{P}P^{-3}$ is the rate of rotational energy loss, I is the neutron star moment of inertia, P is the pulsar period, $\dot{P}$ is its first time derivative, and d is the pulsar distance. In a list of rotation-powered pulsars ordered by $\dot{E}d^{-2}$, all of the top 10 pulsars have been detected at optical or higher frequencies. All but one of these (PSR J0437−4715) are young, with periods of between 16 and 150 ms and relatively large spin-down rates. Only two other young pulsars, PSRs B0656+14 and B1055−52, have been detected at high energies (Ramanamurthy et al. 1996; Thompson et al. 1999), and these lie at 20th and 39th place in the $\dot{E}d^{-2}$ list.

In this Letter we report the discovery of two young pulsars, PSR J1420−6048 and PSR J1837−0604, by the Parkes multibeam pulsar survey. Both of these pulsars are coincident within the uncertainties with γ-ray sources listed in the Third EGRET Catalog (Hartman et al. 1999), 3EG 1420−6038 and 3EG 1837−0606, respectively. Roberts & Romani (1998) have identified several hard X-ray sources within the γ-ray error box for 3EG 1420−6038 and suggest that one of these is a pulsar-powered wind nebula associated with the γ-ray source. Radio images of the region obtained with the Australia Telescope Compact Array (Roberts et al. 1999) show evidence for several potential birth sites for the pulsar.

2. OBSERVATIONS AND RESULTS

An extensive survey of the Galactic plane for pulsars is being carried out using the multibeam receiver on the Parkes 64 m radio telescope (Manchester et al. 2001). Observations are made using dual-polarization receivers in a bandwidth of 288 MHz centered on 1374 MHz. A large filter-bank system gives 96 3 MHz channels for each polarization of each of the 13 beams. Signals from individual frequency channels are detected, added in polarization pairs, high-pass filtered, integrated, and 1 bit–digitized every 250 μs. The excellent system noise temperature (~21 K), large bandwidth, and relatively long integration time of 35 minutes per pointing give a sensitivity limit for long-period pulsars of about 0.2 mJy. Each confirmed pulsar is subjected to a series of timing observations using the center beam of the same receiver system for pulsars south of declination −35° and using a similar system at Jodrell Bank Observatory for most pulsars

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TABLE 1
Measured and Derived Parameters for PSRs J1420−6048 and J1837−0604

Parameter	PSR J1420−6048	PSR J1837−0604
Right ascension (J2000)	14 20 08.237(16)[a]	18 37 43.55(1)
Declination (J2000)	−60 48 16.43(15)[a]	−06 04 49(1)
Pulse period (s)	0.06817995472(1)[b]	0.096293185140(2)
	0.06817987659(2)[c]	…
Period derivative ($\times 10^{-15}$)	82.8523(10)[b]	45.2013(2)
	83.167(3)[c]	…
Pulse frequency (s^{-1})	14.667067529(3)[b]	10.3849509032(2)
	14.667084334(6)[c]	…
Frequency derivative (s^{-2})	$-1.78234(2) \times 10^{-11}$[b]	$-4.87483(2) \times 10^{-12}$
	$-1.78911(7) \times 10^{-11}$[c]	…
Parameter Δ_8	1.0	0.1
Epoch (MJD)	51,600.0	51,487.0
Number of TOAs	24[b]	39
	9[c]	…
Data span (MJD)	51,100–51,523[b]	51,153–51,820
	51,677–51,900[c]	…
rms residual (red/white) (ms)	2.1/0.45[b]	10.3/1.6
Dispersion measure (cm^{-3} pc)	360.0(2)	462(1)
Pulse width at 50% of peak (ms)	9.3	13
Pulse width at 10% of peak (ms)	16	30
Flux density at 1400 MHz (mJy)	0.9(1)	0.4(1)
Galactic longitude (deg)	313.54	25.96
Galactic latitude (deg)	+0.23	+0.26
Surface dipole magnetic field (G)	2.4×10^{12}	2.1×10^{12}
Characteristic age (kyr)	13.0	33.7
Spin-down luminosity (ergs s^{-1})	1.0×10^{37}	2.0×10^{36}
Distance (kpc)	7.7	6.2

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Position obtained from ATCA interferometric observations (see text).
[b] Preglitch solution.
[c] Preliminary postglitch solution.

north of this limit. In the timing observations, the data are dedispersed and synchronously folded at the predicted topocentric pulsar period for ∼1 minute, to form subintegrations, with a total integration time per observation ranging between 2 and 30 minutes, depending on the pulsar flux density. Integrated pulse profiles of each observation are convolved with a high signal-to-noise template to give a topocentric time of arrival (TOA). The program TEMPO[11] is used to convert these to solar system barycentric TOAs at infinite frequency and to perform a multiparameter fit for the pulsar parameters. Barycentric corrections are obtained using the Jet Propulsion Laboratory DE200 solar system ephemeris (Standish 1982).

The discovery of both pulsars was confirmed during 1998 October, and, since then, timing observations have been carried out at Parkes for PSR J1420−6048 and at Jodrell Bank for PSR J1837−0604. Observed and derived parameters from these timing observations are listed in Table 1. Uncertainties given in parentheses are in the last quoted digit and are 1 σ. The position for PSR J1420−6048 was obtained from an 11.5 hr synthesis observation using the 6 km Australia Telescope Compact Array at 1384 and 2496 MHz on 1999 August 20. The array was in the 6D configuration, and pulsar gating mode was used. Calibrators used were PKS 1329−665 and PKS 1934−638 for phase and flux density calibration, respectively. Flux densities for PSR J1420−6048 measured from the on-pulse–off-pulse image were 1.09(8) and 0.61(17) mJy at 1384 and 2496 MHz, respectively. These flux densities imply a spectral index of -1.0 ± 0.6.

For PSR J1420−6048, the position was held at the interferometric value for all timing analyses. There is evidence for significant period irregularities for both pulsars, with significant values for the second and higher derivatives of the pulse frequency. In Table 1, two values for the postfit rms timing residual are given; the first is for the fit of frequency and frequency derivative only, whereas the second is after fitting higher frequency derivatives. The high values of the ratio of these "red" and "white" residuals reflect the large amount of timing noise. For PSR J1837−0604, the position was obtained from the fit including higher order frequency derivatives. We can estimate the cumulative phase contribution over time t due to timing noise using the parameter $\Delta(t) = \log(|\ddot{\nu}|t^3/6\nu)$ introduced by Arzoumanian et al. (1994). Calculating this parameter for $t = 10^8$ s, Arzoumanian et al. (1994) found that most pulsars in their sample conform approximately to the relation $\Delta_8 = 6.6 + 0.6 \log \dot{P}$. The values of the Δ parameter for PSR J1420−6048 and PSR J1837−0604 scaled to $t = 10^8$ s are reported in Table 1. These values are somewhat larger than, but not incompatible with, those predicted. It should be noted that the $\ddot{\nu}$ values in our case are measured over a data span considerably shorter than 10^8 s.

PSR J1420−6048 suffered a glitch of amplitude $\Delta P/P \sim -1.2 \times 10^{-6}$ around MJD 51,600. In Table 1, preglitch and postglitch parameters are given. For both pulsars, the dispersion measure was estimated using observations from Parkes by splitting the observed bandwidth into four subbands and obtaining TOAs for each subband of each observation. These TOAs were then analyzed using TEMPO, holding the astrometric and period parameters fixed at the values obtained in the white solution and fitting for dispersion measure. The distances quoted in the table are calculated from the dispersion measure using the Taylor & Cordes (1993) model. The uncertainty on these distances can be up to ≃25%.

[11] See http://pulsar.princeton.edu/tempo.

The surface dipole magnetic field in Table 1 was computed using $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G; the characteristic age is given by $\tau_c = P/(2\dot{P})$; and, for the spin-down luminosity, $\dot{E}$, the neutron star moment of inertia I is taken to be 10^{45} g cm^2. The distance is derived from the dispersion measure assuming the Taylor & Cordes (1993) distance model.

Mean pulse profiles for the two pulsars at 1374 MHz are given in Figure 1. For PSR J1420−6048, the profile has two broad and relatively widely spaced peaks; the pulse width at half-maximum is about 50° of longitude and, at the 10% level, about 85°. Gil, Kijak, & Seiradakis (1993) and Kramer et al. (1994) derived a beam radius $\sim 5° \times P^{-1/2}$ for two- and three-component pulsars, valid for a pulse width measured at 10% intensity level. Gould (1994) derived a similar relation valid for a pulse width measured at 5% intensity level. These relations predict, in the case of an orthogonal rotator, a pulse width at the 10% level of about 40° for PSR J1420−6048. This is significantly less than the observed value, suggesting that the inclination angle (the angle between the beam axis and the rotation axis) is ∼30°.

The observed profile for PSR J1837−0604 is also wide, but in this case the asymmetric form of the pulse shape suggests that interstellar scattering is the dominant effect. An exponential fit to the trailing edge of the profile in Figure 1 indicates a characteristic scattering time of 10 ± 2 ms at 1.4 GHz, corresponding to 40 ± 8 ms (2 σ uncertainty) at 1 GHz. This is substantially larger than the value of 5 ms predicted by the Taylor & Cordes (1993) model.

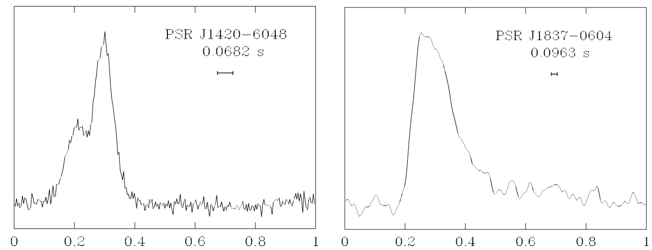

FIG. 1.—Mean pulse profiles for PSR J1420−6048 and PSR J1837−0604 at 1400 MHz recorded at Parkes and Jodrell Bank, respectively. In each case, the whole pulsar period is shown. The horizontal bar under the pulsar period indicates the profile smearing due to dispersion across the filter-bank channels.

3. DISCUSSION

The two pulsars, PSR J1420−6048 and PSR J1837−0604, are young, with characteristic ages of 13 and 34 kyr, respectively, and have high values of the spin-down flux $\dot{E}d^{-2}$, 1.7×10^{35} and 5.2×10^{34} ergs s^{-1} kpc^{-2}, respectively. PSR J1420−6048 is the 11th-ranked pulsar in a list of known rotation-powered pulsars (including Geminga) ordered by $\dot{E}d^{-2}$, whereas PSR J1837−0604 lies at 22d place. All pulsars in the list above PSR J1420−6048 have been detected at optical or higher frequencies, and PSR J1837−0604 lies just two places below PSR B0656+14.

Both pulsars lie within the error contours of previously unidentified γ-ray sources in the Third EGRET Catalog (Hartman et al. 1999). PSR J1420−6048 is located ∼10′ away from the most probable position of 3EG J1420−6038; the 95% confidence area for this source has a radius of ∼19′. PSR J1837−0604 is also about 10′ from the nominal position of 3EG J1837−0606, close to the border of the 95% γ-ray confidence region of radius 11′.4. Such young and energetic pulsars are rare in the known pulsar population, so these positional coincidences are suggestive of physical connections.

The spectral properties of 3EG J1420−6038 and of 3EG J1837−0606 support the identifications. In the range 100 MeV to 10 GeV, the spectra of the two sources can be fitted with power laws of photon spectral index $\gamma = 2.02 \pm 0.14$ and $\gamma = 1.82 \pm 0.14$, respectively, where $dN/dE \sim E^{-\gamma}$. These values are well inside the spectral index range of 1.66–2.19 observed in the sample of the known γ-ray pulsars (Thompson et al. 1999). Integrating the observed spectrum (summed over the four cycles of the EGRET observations), one derives energy fluxes of $(3.3 \pm 0.9) \times 10^{-10}$ and $3.7 \pm 0.9 \times 10^{-10}$ ergs s^{-1} cm^{-2} for the two sources.

Conversion of these flux densities into high-energy luminosity L_γ suffers from two major uncertainties: the distance of the source and the beaming fraction f. Using the distance inferred from the dispersion measure (see Table 1) and assuming isotropic emission ($f = 1$), the implied γ-ray luminosity is ∼23% of the spin-down luminosity in the case of PSR J1420−6048 and ∼85% for PSR J1837−0604. Similar results have been derived for all the known γ-ray pulsars (Rudak & Dyks 1998). Since such high levels of efficiency in the conversion of $\dot{E}$ into L_γ are unlikely, a beaming factor $f = (4\pi)^{-1}$ is usually adopted. For this beaming factor, corresponding to radiation into 1 sr, the luminosity of 3EG J1420−6038 is $(1.9 \pm 0.5) \times 10^{35}$ ergs s^{-1} (at $d = 7.7$ kpc), implying an efficiency of ∼2%, and for 3EG J1837−0606 we have $L_\gamma = (1.4 \pm 0.4) \times 10^{35}$ ergs s^{-1} (at $d = 6.2$ kpc) and efficiency of ∼7%. These efficiencies lie within the range of 0.1%–20% found for other known γ-ray pulsars. They are somewhat higher than those calculated by Thompson et al. (1999) for the Vela pulsar and PSR B1706−44 (0.3% and 2%), which, respectively, have similar characteristic ages to PSR J1420−6048 and PSR J1837−0604. However, they are well within the scatter of the L_γ obtained for other pulsars when plotted against, for example, the Goldreich-Julian current $\dot{N} \sim \dot{E}^{1/2}$ (cf. Fig. 5 of Thompson et al. 1999). The γ-ray luminosity and efficiency of PSR J1420−6048 and Vela could be reconciled by adopting a distance for PSR J1420−6048 smaller than that obtained from the dispersion measure. In fact, a much closer distance ($d \sim 2$ kpc) is suggested by the X-ray observations (M. S. E. Roberts, R. W. Romani, S. Johnston, V. M. Kaspi, & F. Camilo 2001, in preparation).

For 3EG J1837−0606, we note that the EGRET location map is probably inconsistent with a single point source, showing an extension on the side opposite to the radio position of PSR J1837−0604. In this case, the γ-ray luminosity of the pulsar counterpart would be smaller, so the needed efficiency of conversion of rotational $\dot{E}$ into L_γ would also be smaller.

Using a long *ASCA* pointing and the radio ephemeris for PSR J1420−6048, M. S. E. Roberts et al. (2001, in preparation) found marginally significant X-ray pulsations from an unresolved source at the pulsar position. This supports the hypothesis that the observed γ-ray source 3EG J1420−6038 is the pulsar itself, that is, pulsed emission originating in the magnetosphere of the young neutron star. Folding analysis of the archival EGRET γ-ray data at the nominal spin period is not straightforward, because of the uncertainty in the (backward) extrapolation of the ephemeris resulting from the presence of timing noise and the possibility of glitches during the extrapolation period. With a contemporaneous radio ephemeris, this task could easily be accomplished with future missions such as *AGILE* and *GLAST*.

Another possibility is that the high-energy luminosity of 3EG J1420−6038 is produced in a pulsar wind nebula (PWN), as suggested by Roberts & Romani (1998) and Roberts et al. (1999). However, at the distance of $d \sim 2$ kpc proposed by M. S. E. Roberts et al. (2001, in preparation), the 2–10 keV flux from the region surrounding the pulsar appears much fainter than that predicted by Kawai, Tamura, & Saito (1998). Also, Becker et al. (1999) and Pivovaroff, Kaspi, & Gotthelf (2000) do not find any evidence for extended emission around other young pulsars.

Finally, we discuss possible birth sites for these two young pulsars. Although no known supernova remnant (SNR) is contained in the error ellipse of 3EG J1420−6038, radio interferometric observations of this region (Roberts et al. 1999, hereafter R99) show a rather complex structure (designated by R99 as the "Kookaburra") including two nonthermal sources whose radio emission is consistent with that from a PWN. An extended region (designated by R99 as "K3") is compatible with the PSR J1420−6048 position. A plerion candidate G313.3+01 (designated by R99 as the "Rabbit") is located just outside the border of the 95% confidence contour for 3EG J1420−6038 and could be a birth site for PSR J1420−6048 as well. At a distance of $d \sim 2$ kpc proposed by M. S. E. Roberts et al. (2001, in preparation), the required transverse velocity v_t would be $v_t \sim 620(d_{\rm kpc}/2)(\tau_c/13\ {\rm kyr})^{-1}$ km s^{-1}. The only known SNR in proximity to PSR J1420−6048, the shell G312.4−0.4, is located ∼75′ southwest of the pulsar position and partially overlaps another EGRET soft γ-ray source, 3EG J1410−6147; such an association would imply an extremely high transverse velocity $v_t \sim 3200$ km s^{-1}. Very high velocities also are implied by association with the shell G313.0−0.1 (at ∼40′ from the current position of PSR J1420−6048) and the structure designated by R99 as the "wings of the Kookaburra," probably part of an old large shell.

For PSR J1837−0604, there is no known SNR in a circle of 1°.5 around the pulsar position. The field surrounding this pulsar was observed with the Very Large Array in 2000 June and July using the DnC configuration. On-source integration times were 3 hr at a center frequency of 1.4 GHz and 2 hr at 4.8 GHz. These observations show the pulsar to be located on the edge of a large (30′ × 15′) extended shell, which we designate G26.0+0.1. Comparison of our 1.4 and 4.8 GHz images demonstrates that the brightest parts of this shell have an approximately flat spectral index ($\alpha \approx 0$; $S_\nu \propto \nu^\alpha$), while *IRAS* and *Midcourse Space Experiment* data on the region show a bright infrared shell with a similar morphology to that seen in the radio (Roberts et al. 2000). Furthermore, the brightest parts of G26.0+0.1 have been detected in various hydrogen recombination lines (e.g., Wink, Wilson, & Bieging 1983). All these results strongly suggest that G26.0+0.1 is an H II region. The systemic velocity of G26.0+0.1 of ∼110 km s^{-1} corresponds to possible kinematic distances of 6 or 9 kpc. The former is consistent with the distance estimated for the pulsar, and it is possible that both sources are associated with the same group of massive stars. The absence of an SNR associated with PSR J1837−0604 is not surprising. SNRs in or near bright H II regions are difficult to identify (Sarma et al. 1997). Even in unconfused regions, many relatively young pulsars have no detectable associated SNR (e.g., Pivovaroff et al. 2000). A supernova blast wave expanding into a low-density environment (Kafatos et al. 1980; Gaensler & Johnston 1995) or an early fading of the SNR could be an explanation. We have also examined the region immediately surrounding the pulsar to search for any evidence of an associated PWN. We find no evidence for such a nebula at either 1.4 or 4.8 GHz. Compared with the deep searches for PWNs carried out toward other pulsars (Gaensler et al. 2000), our limiting sensitivity is however unconstraining because of confusion from G26.0+0.1.

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