DISCOVERY OF THE YOUNG, ENERGETIC RADIO PULSAR PSR J1105–6107

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ABSTRACT

We report the discovery and follow-up timing observations of the 63 ms radio pulsar, PSR J1105–6107. The pulsar is young, having a characteristic age of only 63 kyr and, from its dispersion measure, is estimated to be at a distance of ~7 kpc from the Sun. We consider its possible association with the nearby supernova remnant G290.1–0.8 (MSH 11–61/A); an association requires that the proper motion of the pulsar be ~22 mas yr⁻¹ (corresponding to ~650 km s⁻¹ for a distance of 7 kpc) directed away from the remnant center, assuming that the characteristic age is the true age. The spin-down luminosity of the pulsar, 2.5 × 10³⁶ ergs s⁻¹, is in the top 1% of all known pulsar spin-down luminosities. Given its estimated distance, PSR J1105–6107 is therefore likely to be observable at high energies. Indeed, it is coincident with the known CGRO/EGRET source 2EG J1103–6106; we consider the possible association and conclude that it is likely.

Subject headings: gamma rays: observations — pulsars: individual: (PSR J1105–6107) — stars: neutron — supernova remnants

1. INTRODUCTION

We have discovered a 63 ms radio pulsar, PSR J1105–6107, during a recent search for pulsars using the 64 m radio telescope at Parkes, New South Wales, Australia. Most pulsars with similar rotation periods fall into one of two categories: those that are young and energetic, the short spin period a result of a relatively recent birth, or those that have been mildly recycled by a binary companion, like the original binary pulsar, PSR B1913 + 16, which has a spin period of 59 ms. Thus, a 63 ms radio pulsar is an important find, worthy of further investigation.

Here we report on the discovery and follow-up timing observations of PSR J1105–6107 and show that it is a member of the first category above, namely young and energetic. Pulsars are hypothesized to have been born in supernovae; the existence of a young pulsar, therefore, requires us to consider whether there is an associated remnant of a supernova explosion. In the case of PSR J1105–6107, we consider its possible association with the known remnant G290.1–0.8 (MSH 11–61/A) which lies nearby on the sky. In addition, the existence of an energetic pulsar requires us to consider whether there should be associated high-energy emission, generally representing a significant fraction of the spin-down luminosity of the pulsar, very likely holds clues to the yet-elusive pulsar emission mechanism. We show that PSR J1105–6107 should be detectable at high energies, and consider whether the known EGRET γ-ray source 2EG J1103–6106 is associated with the pulsar.

2. OBSERVATIONS AND RESULTS

PSR J1105–6107 was discovered with the Parkes telescope in 1994 July in a search at a central radio frequency of 1420 MHz. The search targeted OB runaway stars in the hope of detecting new pulsar/OB star binaries. PSR J1105–6107 was discovered while pointing at the B4 V star HD 96264, but the follow-up observations described below rule out any association. The details of the search will be described elsewhere (Kaspi, Manchester, & D’Amico 1997).

A total of 96 timing observations of PSR J1105–6107 were obtained between 1993 July 8 and 1996 July 4 at Parkes. Of these, 91 were obtained at central radio frequencies ranging from 1390 to 2050 MHz. The remaining five observations were obtained at 660 MHz in 1995 July. All data taken before 1995 were obtained using filter-bank timing systems (2 × 64 × 5 MHz at 1520 MHz and 2 × 256 × 0.125 MHz at 660 MHz) that have been described in detail elsewhere (e.g., Bailes et al. 1994). Most data from after 1995 were obtained using the Caltech

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correlator-based pulsar timing machine (Navarro 1994), which has $2 \times 128$ lags across 128 MHz in each of two separate frequency bands. Typically, correlator observations were made at central frequencies of 1420 and 1650 MHz simultaneously. Compared to the filter-bank system, the narrower frequency channels of the correlator resulted in less channel dispersion smearing and, hence, finer time resolution. Filter-bank data were recorded on tape and folded off-line; correlator data were folded on-line. Average profiles were convolved with high signal-to-noise ratio templates to yield pulse arrival times. The average profile at 1650 MHz shown in Figure 1 was obtained by aligning and summing numerous individual correlator profiles. The profile at 1420 MHz is similar, while the two components obvious in Figure 1 cannot be resolved in the 660 MHz data because of dispersion smearing. Resulting arrival times were analyzed using the standard TEMPO pulsar timing software package (Taylor & Weisberg 1989) together with the JPL DE200 ephemeris (Standish 1982). Typical arrival time uncertainties were $\sim 250 \mu s$ for $\sim 10$ minute integrations with signal-to-noise ratio $\sim 20$ at frequencies above 1390 MHz. Arrival times at 660 MHz had uncertainties approximately twice as large.

In the timing analysis, the pulsar dispersion measure (DM) was first determined from delays across the observed bands and then refined using 15 arrival times measured in 1995 July, including all five measured at 660 MHz. This was to ensure good frequency coverage and no contamination from long-term timing noise, we "prewhitened" the data (see, e.g., Kaspi, Taylor, & Ryba 1994), fitting for sufficiently many frequency derivatives (four) to render the residuals approximately Gaussian distributed, determined by eye. The timing position, determined while fitting for these derivatives, is given in Table 1 and was subsequently held fixed. Finally, we measured the best period and period derivative, also given in Table 1. The uncertainties in all parameters are 1 $\sigma$ statistical uncertainties, obtained assuming equal weighting for all arrival times. The surface magnetic field of the pulsar $B = 3.2 \times 10^{19} G (P P)^{1/2} \approx 1 \times 10^{12} G$, and its spin-down luminosity $\dot{E} = 4\pi^2 I P / P^3 \approx 2.5 \times 10^{36}$ ergs s$^{-1}$, where the neutron star moment of inertia $I$ is taken to be $10^{45}$ g cm$^2$. The characteristic age of the pulsar $\tau_c \equiv P / 2 \dot{P} \approx 63$ kyr.

Postfit residuals, obtained after removing the timing model given in Table 1, are shown in Figure 2. In the plot, uncertainties on arrival times are typically smaller than the size of the symbols.

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**TABLE 1**

| Parameter                     | Value                  |
|-------------------------------|------------------------|
| Right ascension, $x$ (J2000)  | $11^h 05^m 26^s 07^s (7)$ |
| Declination, $\delta$ (J2000) | $-61\degree 07\arcmin 52\arcsec 14^s (4)$ |
| Galactic latitude, $l$        | 290.4896(2)            |
| Galactic longitude, $b$       | $-0\degree 8465(1)$    |
| Period, $P$                   | 0.063191252792(3) s    |
| Period derivative, $\dot{P}$  | $15.80466(12) \times 10^{-15}$ |
| Dispersion measure, DM        | 271.01(2) pc cm$^{-3}$ |
| Epoch of period               | MJD 49545.0000         |
| rms timing residual           | 6.2 ms                 |
| Surface magnetic field strength, $B$ | $1.0 \times 10^{12}$ G |
| Characteristic age, $\tau_c$  | 63.350 yr              |
| Spin-down luminosity, $\dot{E}$ | $2.5 \times 10^{36}$ ergs s$^{-1}$ |
| Flux density at 660 MHz$^a$   | $4.1(7)$ mJy           |
| Flux density at 1420 MHz$^b$  | $1.84(14)$ mJy         |
| Flux density at 1650 MHz$^c$  | $1.58(6)$ mJy          |
| Spectral index                | $-1.36(1)$             |
| 50% width at 1650 MHz, W50     | 3.4 ms = 53.9 mP       |
| 10% width at 1650 MHz, W10     | 4.8 ms = 76.0 mP       |

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*a* Reported flux is the mean of those measured at 3 epochs.  
*b* Reported flux is the mean of that measured at 24 epochs.  
*c* Reported flux is the mean of that measured at 16 epochs.
symbol. The timing noise, interpreted as irregularities in the neutron star’s rotation, is obvious. We can quantify the amount of timing noise, as prescribed by Arzoumanian et al. (1994), by measuring $\Delta_{\alpha} = \log \left( \frac{\nu}{r^2/\nu} \right)$, where $\nu = 1/P$ and for $r = 10^8$ s. For PSR J1105–6107 we find $\Delta_{\alpha} = -0.8$, which is consistent within the scatter with $\Delta_{\alpha}$ parameters for other young pulsars. The pulsar’s small as well as the large amount of timing noise, suggest that PSR J1105–6107 is an excellent candidate for glitches. Indeed, we cannot rule out some contamination of the timing parameters by a slowly relaxing glitch that occurred before 1993 July (see Manchester et al. 1991; Lyne et al. 1996a).

That the timing observations for PSR J1105–6107 reported here extend back a full year before the discovery of the pulsar requires some explanation. In general, raw, dispersed, and unfolded filter-bank timing data are recorded and archived on tape. By chance, PSR J1105–6107 lies less than one Parkes 1420 MHz primary beamwidth from the pulsar PSR J1103–6101, which was discovered in 1992 July as part of a major search for pulsars near supernova remnants (Kaspi et al. 1996). The DM toward PSR J1103–6101 is only 75 pc cm$^{-3}$, indicating that it is a foreground object. Once the discovery of PSR J1105–6107 was made and its proximity to PSR J1105–6101 realized, the archived raw data for the latter were retrieved, redispersed, and folded at the parameters of the former.  

3. DISCUSSION

3.1. Possible Association with G290.1–0.8

PSR J1105–6107 is located near the Galactic supernova remnant G290.1–0.8, also known as MSH 11–61A (Shaver & Goss 1970). The proximity of a young pulsar to a supernova remnant suggests that they may have been formed in the same explosion. Alternatively they may be coincidentally superposed on the sky; the Galactic plane is replete with pulsars and supernova remnants, and the possibility of chance alignment is nonnegligible. Indeed a spurious association is not implausible, as the true remnant of the pulsar’s birth may well have faded from view (Braun, Goss, & Lyne 1989), and the explosion that produced G290.1–0.8 may not have produced a neutron star. Here we consider whether there is a genuine association between PSR J1105–6107 and G290.1–0.8.

The Taylor & Cordes (1993) DM-distance model places PSR J1105–6107 at a distance of 7 kpc, given its DM and Galactic coordinates. The uncertainty on this distance is estimated to be $\sim 25\%$. Thus, the range consistent with the DM-distance model is 5–9 kpc. Regions of enhanced free-electron density (like H II regions) along the line of sight can result in an overestimate of the pulsar’s distance from its DM.

The distance to G290.1–0.8 has been estimated many times in the literature. First, H I absorption measurements made by Dickel (1973) suggest that the remnant is probably at 3–4 kpc. The $\Sigma-D$ relation, which is known to be very uncertain, suggests a distance of 3–6 kpc (Clark & Caswell 1976). Other authors have suggested that the remnant is more distant (12–14 kpc) on the basis of its optical morphology and H$\alpha$ to S$\beta$ ratio, which are more typical of older (hence larger) remnants like the Monoceros Ring (Elliott & Malin 1979; Kirshner & Winkler 1979). More recently, Rho (1995) concluded from the neutral hydrogen absorption component of the X-ray spectrum of the remnant (see below) that the distance is $\sim 7$ kpc, consistent with the pulsar distance, although this method has large uncertainties. Independently, Rosado et al. (1997) argued that the remnant must be at $\sim 7$ kpc on the basis of the kinematics of the optical emission, although they too concede that the estimate is uncertain given the complexity of the field. Thus, overall, the estimated distances to the remnant are generally consistent with that of the pulsar within the substantial uncertainties; an association is therefore plausible.

The age $\tau$ of a radio pulsar is given by

$$\tau = \frac{P}{(n-1)P} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right],$$

(1)

where $P$ is its current spin period, $P_0$ is its spin period at birth, and $n$ is its braking index. The braking index $n$ is defined by the pulsar spin-down $\dot{\nu} = -K\nu^n$, where $\nu = 1/P$, and $K$ is a positive constant that depends on the magnetic dipole moment and moment of inertia of the rotating neutron star (Manchester & Taylor 1977). It is easy to show that $n = \nu \dot{\nu}/\nu^2$ and, hence, can be determined from timing observations in the absence of strong timing noise. The characteristic age is defined as $\tau_c = P/2\dot{P}$, which assumes that $n = 3$ (true for a simple dipole) and $P_0 \ll P$. For PSR J1105–6107, $\tau_c = 63$ kyr. However, the short spin period for PSR J1105–6107 compared with other, younger pulsars (e.g., PSR B1509–58, $\tau_c = 1.5$ kyr, $P = 150$ ms) suggests that $P_0 \ll P$ does not necessarily hold in this case and that the true age may be smaller. Alternatively, if the braking index $n < 3$, as is the case for all pulsars for which it has been measured, then $\tau_c$ is an underestimate. Notable is the recent measurement by Lyne et al. (1996b) of $n = 1.6 \pm 0.4$ for the Vela pulsar. Figure 3 shows how the true age of PSR J1105–6107 depends on $P_0$, for four values of $n$. For small $P_0$, the age of the pulsar may be anywhere between 63 and 250 kyr. For $P_0 \approx P$, the pulsars’s age must be smaller than 63 kyr, independent of $n$. If we assume the pulsar was born with a spin period of $\sim 20$ ms, as for the Crab pulsar, then $63 < \tau < 110$ kyr.

Age estimates for the remnant depend strongly on its distance. Milne et al. (1989) estimated the remnant to be only 2.2 kyr old, assuming the smallest distance estimate. Rho (1995) suggests the remnant is somewhat older, $\sim 10$ kyr. The resemblance of the optical emission to that of the Monoceros Ring, the age of which is $\sim 50$ kyr (Leahy, Naranan, & Singh 1986), suggests a much larger age for G290.1–0.8. If it is associated with PSR J1105–6107, the most likely range of true pulsar ages requires the remnant to have an age significantly larger than the Milne et al. (1989) estimate, more in line with the more recently suggested hypotheses that it is at a greater distance.

Figure 4 shows the location of the pulsar with respect to the remnant (from Whiteoak & Green 1996). It lies just over two remnant radii from the approximate remnant geometric center. Its location, well outside the remnant boundaries,
argues against an association (Gaensler & Johnston 1995). However, for a distance of 7 kpc, and assuming the age of the system to be 63 kyr, the transverse velocity of the pulsar, if it is associated with the remnant, is \( \sim 650 \text{ km s}^{-1} \), larger than the mean pulsar transverse velocity (Lyne & Lorimer 1994) but much less than has been suggested for pulsars in other proposed associations (e.g., Frail & Kulkarni 1991; Manchester et al. 1991; Caraveo 1993) and well within the range of measured pulsar velocities (Lyne & Lorimer 1994). Thus, that the pulsar lies well outside the remnant does not necessarily rule out an association; it would require the pulsar transverse velocity to exceed the mean remnant expansion velocity by more than a factor of 2, not unreasonable if the remnant is expanding into a dense environment, as is suggested by its axisymmetric morphology. Radio maps of the region closer to the pulsar show no evidence for any emission that might suggest another, closer supernova remnant or a bow shock nebula (A. Green 1996, private communication). Perhaps interestingly, the pulsar’s inferred trajectory approximately bisects the remnant along its line of symmetry.

Seward (1990) and Rho (1995) presented X-ray images of G290.1–0.8 that show that the emission is centrally peaked. This is in contrast to the radio morphology, which is more shell-like. This suggests that G290.1–0.8 is like the...
supernova remnant W44 (Rho et al. 1994), which, like W28 and 3C400.2 (Long et al. 1991), has centrally peaked X-ray emission but shell-like radio morphology. The central X-ray emission in these remnants is thermal. One possible interpretation is that the emission is due to the evaporation of dense cloudlets that survived the initial blast wave, rather than a central neutron star, as is the case for remnants with centrally peaked radio and nonthermal X-ray emission, such as the Crab nebula. Since the morphology suggests that this is also true of G290.1—0.8, there is no evidence for a central point source that would argue against an association with PSR J1105—6107. We note also that W44, W28, and 3C400.2 are relatively old remnants, all having estimated ages greater than 10 kyr.

A measurement of the proper motion for PSR J1105—6107 is highly desirable for determining whether it is associated with G290.1—0.8. If the association is real, the pulsar proper motion should be \( \sim 22 \) (63 kyr/\( r \)) mas yr\(^{-1} \), independent of the distance. A timing proper motion will not be forthcoming, given the large amount of timing noise exhibited by the pulsar (Fig. 2). Also, its low flux density (see Table 1) will make interferometric observations using currently available telescopes difficult, although pulse gating may improve the feasibility. A measurement of the pulsar’s scintillation speed through observations of its radio dynamic spectrum, a technique recently used by Nicastro, Johnston, & Koribalski (1996) to argue against an association between the radio pulsar PSR B1706—44 and the supernova remnant G343.1—2.3, may provide some evidence against an association if a small speed is found. However, this will be difficult again because of the pulsar’s low flux density. A large pulsar velocity away from the remnant could be confirmed by the presence of H\(_{\alpha} \) emission from a bow shock nebula (see Cordes, Romani, & Lundgren 1993), although a lack of such emission could be due to an absence of ambient neutral hydrogen and would not disprove an association.

3.2. Possible Association with \( \gamma \)-Ray Source 2EG J1103—6106

At a distance of 7 kpc, given its large spin-down luminosity (Table 1), PSR J1105—6107 ranks 19th in a list of rotation-powered pulsars ordered by \( E/\dot{E}^{2} \). Six of the seven top spots are held by known \( \gamma \)-ray pulsars (the seventh being the millisecond pulsar PSR J0437—4715), while most of the top 30 are known X-ray sources. On this list, PSR J1105—6107 ranks 15 spots higher than the known X-ray and \( \gamma \)-ray pulsar PSR B1055—52 (Cheng & Helfand 1983; Fierro et al. 1993). Thus, PSR J1105—6107 is a good candidate to be an observable high-energy emitter.

In fact, the radio timing position of PSR J1105—6107 (Table 1) lies well inside the 95% confidence 49\( ^{\circ} \times 32 \) error ellipse of the second EGRET catalog source 2EG J1103—6106 (Thompson et al. 1995). This \( \gamma \)-ray source was referred to in the first EGRET catalog as GRO J1110—60 (Fichtel et al. 1994) and is near, but outside, the error box of the second COS B catalog source 2CG 288—00 (Swanenburg et al. 1981). Reported \( E > 100 \) MeV fluxes of 2EG J1103—6106 show no evidence for significant variability, consistent with its interpretation as a rotation-powered pulsar (Thompson et al. 1995; Ramanamurthy et al. 1995). If the sources are associated, the estimated mean flux of 2EG J1103—6106 suggests that PSR J1105—6107 converts approximately 3% of its spin-down luminosity to high-energy \( \gamma \)-rays for a beaming angle of 1.0 sr, comparable with the efficiencies of the Vela pulsar and PSR B1706—44 (Thompson et al. 1992; Grenier, Hermsen, & Clear 1988).

There are 18 radio pulsars for which pulsations have not yet been detected by EGRET that are within 10\( ^{\circ} \) of the Galactic plane and have higher \( E/\dot{E}^{2} \) than PSR B1055—52, omitting millisecond pulsars. With the discovery of PSR J1105—6107, four of these lie within the 99% confidence contours of unidentified EGRET sources. By contrast, of 268 known radio pulsars within 10\( ^{\circ} \) of the Galactic plane with energetics that should be below the EGRET threshold for detection, only two lie within the 99% confidence contours of unidentified EGRET sources (Fierro 1995). Assuming that this control group is spatially distributed like the young pulsars, using Poisson statistics the probability for four coincidences among the 18 energetic pulsars is \( \sim 1 \times 10^{-9} \). Even conservatively accounting for the possibility that the control group is less concentrated near the Galactic plane (for example, by assigning it a significantly larger mean z-height), we find that the probability for four coincidences must be under \( \sim 1\% \), although exact probabilities are difficult to estimate given the uncertainties in pulsar distances and spatial distributions and in unidentified EGRET source properties. Even so, the evidence argues strongly that at least three of the four coincidences of high \( E/\dot{E}^{2} \) pulsars with the unidentified EGRET sources are real. Furthermore, Yadigaroglu & Romani (1997) showed that most of the unidentified low-latitude EGRET sources such as 2EG J1103—6106 are likely to be young pulsars like PSR J1105—6107. We therefore conclude that the association between PSR J1105—6107 and 2EG J1103—6106 is likely. However, only the detection of \( \gamma \)-ray pulsations at the radio period will demonstrate the association unambiguously.

Several authors have argued that the \( \gamma \)-ray source 2EG J1103—6106 as well as GRO J1110—60 and 2CG 288—00 are associated with the Carina complex, which includes the peculiar star \( \eta \) Car, open clusters Tr 16 and Tr 14, and several OB associations, with the \( \gamma \)-rays being produced by cosmic-ray interactions in the intercluster gas or by \( \eta \) Car itself (Morfill, Forman, & Bignami 1984; Borgwald & Friedlander 1993; Manchanda et al. 1996). The identification of 2EG J1103—6106 with PSR J1105—6107 does not necessarily preclude these interpretations, since 2EG J1103—6106 may be a composite of several sources. Indeed, there is marginal evidence that its emission is extended (Swanenburg et al. 1981; Thompson et al. 1995). Nevertheless, the discovery of a luminous young pulsar near the \( \gamma \)-ray source casts some doubts on alternative interpretations. Sturmer & Dermer (1995) suggested that GRO J1110—60 is associated with the supernova remnant G291.0—0.8 (MSH 11—62), with the emission a result of cosmic-ray interactions with the remnant. With the revisions made in the second EGRET catalog, the source is now closer to the position of PSR J1105—6107 and G290.1—0.8; this and the discovery of PSR J1105—6107 suggest that their proposed model is not relevant to this particular \( \gamma \)-ray source.

Kaaret & Cottam (1996) suggested that 2EG J1103—6106 is a young pulsar associated with the OB association Car 2. The measured distance to the association is 2.2 kpc (Mel’nik & Efremov 1995), which is inconsistent with the DM-derived distance of 7 kpc for PSR J1105—6107, suggesting that the association lies in the foreground. If the pulsar actually is in the cluster, its association...
with G290.1—0.8 is doubtful because the remnant dimensions would suggest that it is much younger than the pulsar; it would be hard to understand the pulsar’s position so far outside the remnant, since the latter would have had less time to decelerate. In this case, the pulsar should be a bright X-ray source with X-ray luminosity ~2 × 10^{-11} ergs s^{-1} cm^{-2} (Seward & Wang 1988) and should be easily detected by X-ray satellites such as *ASCA*.

4. CONCLUSIONS

We have reported the discovery and follow-up timing observations of PSR J1105—6107, which show it to be young and energetic. We have considered its proximity to the supernova remnant G290.1—0.8 and show that an association between the two is possible and could be confirmed or disproved by proper-motion measurements. We have also considered a possible association of PSR J1105—6107 with the EGRET source 2EG J1103—6106 and conclude that it is likely.

It is remarkable that this interesting pulsar was found serendipitously in a search unrelated to either EGRET sources or supernova remnants, while recent targeted searches of both have been done but have met very limited success. (e.g., Kaspi et al. 1996; Gorham et al. 1996; Nice & Sayer 1997). That PSR J1105—6107 was missed by a survey including G290.1—0.8 is not surprising given the pulsar’s low flux density and large angular displacement from the remnant. If the association between PSR J1105—6107 and G290.1—0.8 is one day proven, it, and other plausible pulsar/SNR associations in which the pulsar lies outside the remnant boundaries (see Kaspi 1996 for a review), would argue strongly that care must be taken to search a large area around the remnant, not just inside. Either way, the discovery of PSR J1105—6107 suggests that deeper searches of the error boxes of unidentified EGRET sources for radio pulsars are warranted.

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