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THE VERY YOUNG RADIO PULSAR J1357−6429

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ABSTRACT

We report the discovery of a radio pulsar with a characteristic age of 7300 yr, making it one of the 10 apparently youngest Galactic pulsars known. PSR J1357−6429, with a spin period of $P = 166$ ms and spin-down luminosity of 3.1×10^{36} ergs s^{-1}, was detected during the Parkes multibeam survey of the Galactic plane. We have measured a large rotational glitch in this pulsar, with $\Delta P/P = -2.4 \times 10^{-6}$, similar in magnitude to those experienced occasionally by the Vela pulsar. At a nominal distance of only ~2.5 kpc, based on the measured free electron column density of 127 cm^{-3} pc and the electron distribution model of Cordes & Lazio, this may be, after the Crab, the nearest very young pulsar known. The pulsar is located near the radio supernova remnant candidate G309.8−2.6.

Subject headings: ISM: individual (G309.8−2.6) — pulsars: individual (PSR J1357−6429)

1. INTRODUCTION

A supernova (SN) explodes in the Galaxy every ~100 yr (see, e.g., Cappellaro 2003, 2004 and references therein). As a result, young neutron stars in their various guises are rare, as are young pulsars. Nevertheless, the payoff resulting from their study can be large, in areas as varied as the physics of core collapse, the internal structure of neutron stars, and magnetospheric emission processes. Also, the youngest neutron stars are often embedded in compact nebulae powered by relativistic pulsar winds or otherwise interact with their host supernova remnants (SNRs)—as such they can make for magnificent probes of their immediate environment. Young pulsars are also particularly useful for establishing reliable birthrates of this important branch of outcomes of core-collapse SNe. For these reasons, substantial effort continues to be devoted to the detection of the youngest neutron stars, and three-quarters of the Galactic pulsars known with an age $\tau < 10$ kyr have been discovered in the past 7 yr at radio and X-ray wavelengths.

In this Letter, we announce the discovery of PSR J1357−6429, a very young, relatively energetic and nearby pulsar, present its rotational history during a span of 4.5 yr that includes a large glitch, and comment on the immediate environment of the pulsar and in particular on a nearby SNR candidate.

2. DISCOVERY AND OBSERVATIONS OF PSR J1357−6429

PSR J1357−6429, with a period $P = 166$ ms, was discovered on 1999 October 7 in data collected during the course of the Parkes multibeam survey of the Galactic plane (e.g., Manchester et al. 2001). This survey employs a 13 beam low-noise receiver system at a central radio frequency of 1374 MHz with a recorded bandwidth of 288 MHz. The large area covered by one pointing enables the 35 minute–long individual integrations that, together with the high instantaneous sensitivity, result in the good limiting flux density of about 0.2 mJy for long-period pulsars over a large area along the Galactic plane ($|b| < 5°$; $260° < l < 50°$). In turn, this has led to the discovery of more than 700 pulsars (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003; Hobbs et al. 2004).

After discovery, as with every newly detected pulsar, we began regular timing observations of PSR J1357−6429 at Parkes, using the filter-bank–based observing system employed in the survey. Typically this consists of the recording to magnetic tape of raw data for about 15 minutes in order to obtain offline a pulse profile from which we derive the time of arrival (TOA) of a fiducial point on the profile by cross-correlation with a high signal-to-noise ratio template. The average pulse shape consists of a single approximately symmetric peak with FWHM = 15 ms (0.09*P*). In this manner, we obtained 125 TOAs spanning the MJD range 51,458–53,104, a period of 4.5 yr.

Using the initial set of TOAs together with the TEMPO timing software,[8] we obtained a phase-connected solution for the pulsar accounting for every turn of the neutron star. In short order, it became apparent that this pulsar has a large period derivative and therefore a very small characteristic age, $\tau_c \equiv P/2\dot{P} =$ 7300 yr. Some 18 months after we began timing the pulsar, on about MJD 52,000, it underwent a very large rotational glitch, with a fractional period spin-up of two parts in 1 million (see Fig. 1 for the evolution of spin parameters over time). In magnitude, this is typical of the glitches that the ≈10 kyr–old Vela pulsar experiences every few years, but interestingly, there is no evidence for an exponentially decaying component as is observed in the Vela glitches (e.g., Dodson et al. 2002).

It is not possible to track the rotation phase of the neutron star across this large glitch. We find that fitting a timing model to the full 3 yr data set since the glitch shows a large quasi-periodicity in the residuals with a ~500 day period, probably due to "timing noise." This can be largely absorbed with a fit requiring a total of six frequency derivatives to whiten the data. For simplicity and to aid observers, the solution we present in Table 1 is based on the most recent 1 yr worth of data, requiring only two derivatives, with the second frequency derivative representing the amount of timing noise. We also provide the net

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

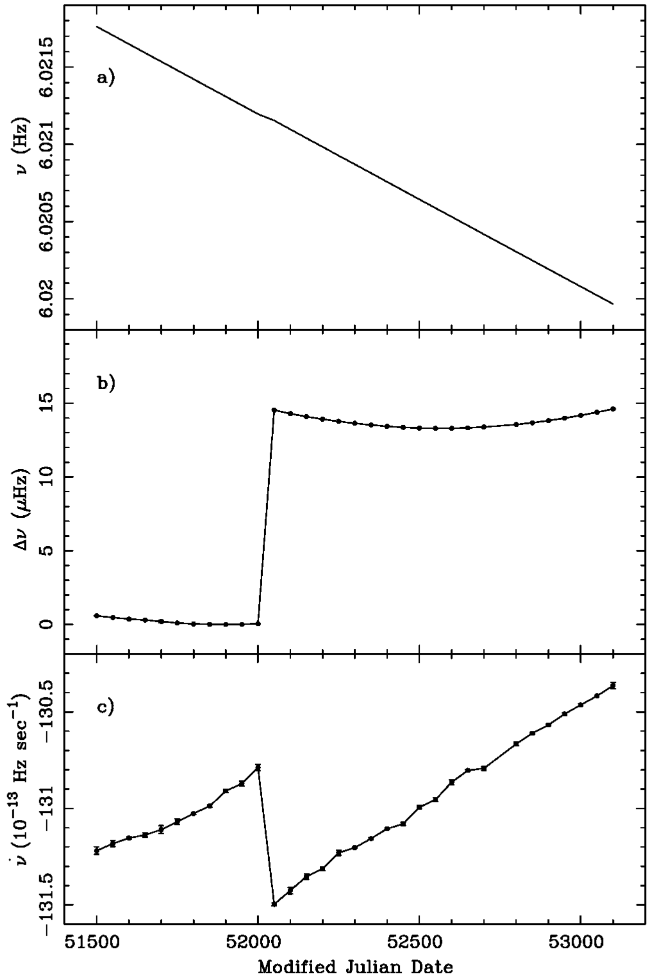

FIG. 1.—Spin history of PSR J1357−6429. The frequency (ν) evolution is shown in panels *a* and *b*, the latter with an expanded scale after removal of ν and $\dot{\nu}$ fitted to the 100 days just prior to the glitch that occurred between MJD 52,005 and MJD 52,037. The error bars are too small to see in these panels. Panel *c* shows the run of $\dot{\nu}$, obtained from fits at 50 day intervals using approximately 100 day sections of data. The discontinuity in $\dot{\nu}$ at the glitch (0.5% of $\dot{\nu}$) reverses about 2 yr worth of change in $\dot{\nu}$ prior to or after the glitch. However, these "continuous" changes in $\dot{\nu}$ (the slopes in panel *c*) are not stationary but are rather likely due to a stochastic process involving the irregular transfer of angular momentum from the interior to the crust of the neutron star (see §§ 2 and 4 and also, e.g., Alpar et al. 1984 and Andersson et al. 2003).

jump in spin parameters at the glitch epoch. We emphasize that the value of $\ddot{\nu}$ is *not* deterministic (see also Fig. 1). It yields an apparent braking index of rotation $n = \nu\ddot{\nu}/\dot{\nu}^2 \approx 40$ (where n is defined by $\dot{\nu} \propto -\nu^n$), which is about 15 times larger than the expected long-term deterministic value.

The presence of significant amounts of timing noise in PSR J1357−6429 is a presumed consequence of the less-than-perfect rotational stability of the young, hot neutron star with a complex superfluid interior (e.g., Bildsten & Epstein 1989; Arzoumanian et al. 1994; D'Alessandro & McCulloch 1997). Such noise biases the pulsar position obtained through timing methods. However, we did not have to rely on timing measurements to obtain the position, since we performed a pulse-gated interferometric observation with the Australia Telescope Compact Array (ATCA) on 2000 August 29. This 5 hr observation used the array in its 6A configuration, giving a maximum baseline of 6 km, with a central frequency of 1376 MHz and a bandwidth of 128 MHz.

TABLE 1

Measured and Derived Parameters for PSR J1357−6429

Parameter	Value
Measured Parameters	
Right ascension (J2000.0)	$13^h57^m02\overset{s}{.}43(2)$[a]
Declination (J2000.0)	$-64°29'30\overset{''}{.}2(1)$[a]
Rotation frequency, ν	6.0201677726(4) s^{-1}
Frequency derivative, $\dot{\nu}$	$-1.305395(4) \times 10^{-11}$ s^{-2}
Second frequency derivative, $\ddot{\nu}$	$1.16(2) \times 10^{-21}$ s^{-3}[b]
Spin period, P	0.16610832750(1) s
Period derivative, $\dot{P}$	$3.60184(1) \times 10^{-13}$
Epoch	MJD 52,921.0
rms residual (whitened)	0.8 ms
Epoch of glitch	MJD 52,021 ± 16
Frequency step at glitch, $\Delta\nu$	$1.46(1) \times 10^{-5}$ s^{-1}[c]
Change in $\dot{\nu}$ at glitch, $\Delta\dot{\nu}$	$-7.02(3) \times 10^{-14}$ s^{-2}[c]
Dispersion measure, DM	127.2(5) cm^{-3} pc
Flux density at 1374 MHz, S_{1400}	0.44(5) mJy
Pulse profile FWHM, w_{50}	15 ms
Pulse width, 10% maximum amplitude, w_{10}	31 ms
Derived Parameters	
Surface magnetic field, B	7.8×10^{12} G
Characteristic age, τ_c	7.3 kyr
Spin-down luminosity, $\dot{E}$	3.1×10^{36} ergs s^{-1}
Distance, d	~2.5 kpc
Radio luminosity at 1400 MHz, $S_{1400}d^2$	~2.7 mJy kpc^2

NOTES.—Figures in parentheses (except those for position) are twice the nominal 1 σ TEMPO uncertainties in the least-significant digits quoted. The timing fit is based on data collected over MJD 52,737–53,104.

[a] Position is obtained from interferometric ATCA observations.

[b] This parameter is not stationary (see § 2 for details; see also Fig. 1).

[c] Assumed glitch epoch for this fit is MJD 52,021. The error in $\Delta\nu$ is dominated by the uncertainty in this epoch.

The interferometric pulsar position, determined from an image made by subtraction of an off-pulse data set from an on-pulse data set, is given in Table 1 and was used for all timing fits.

3. THE AGE, DISTANCE, AND VICINITY OF PSR J1357−6429

The actual age of PSR J1357−6429, assuming a constant magnetic moment, is $\tau = 2\tau_c[1 - (\nu/\nu_0)^{n-1}]/(n-1)$, where ν_0 is the initial rotation frequency of the neutron star. We do not know the actual braking index of the pulsar. However, if it lies in the range $2 \lesssim n \lesssim 3$, as is the case for all four pulsars with n measured via phase-coherent timing (see Camilo et al. 2000 and references therein), then the real age is still $\tau \lesssim 15$ kyr and may be less than 10 kyr, depending on the actual values of n and ν_0. Also, while such youth is not required by the occurrence of the large glitch (e.g., Hobbs et al. 2002), it is certainly consistent with it. There is therefore no doubt that PSR J1357−6429 is a very young pulsar, one of the ~10 youngest known in the Galaxy (see Table 2).

PSR J1357−6429 is also apparently nearby: according to the Cordes & Lazio (2002) model for the Galactic free electron distribution and our dispersion measure, the distance is $d = 2.5$ kpc. The Taylor & Cordes (1993) model yields $d \sim 4$ kpc, suggesting the order of the uncertainty inherent in such estimates. The implied distance of the pulsar away from the Galactic plane is 100–200 pc. In any case, this pulsar appears to be one of the two or three nearest to the Earth among those known with $\tau \lesssim 10$ kyr. Considering, furthermore, that all known pulsars apparently younger than PSR J1357−6429 are associated with a pulsar wind nebula (PWN) or an SNR, it seems reasonable to expect that this might also be the case with PSR J1357−6429.

Figure 2 shows the area around PSR J1357−6429 as seen

TABLE 2

Parameters for All Galactic Pulsars Known with Apparent Ages of Less Than 10 kyr

Pulsar	SNR/PWN	P (ms)	log age[a] (yr)	log $\dot{E}$[b] (ergs s^{-1})	d (kpc)	Wave Band[c]	$L_{\rm X,\,PWN}$[d] ($10^{-3}\dot{E}$)	$L_{\rm X,\,PSR}$[d] ($10^{-3}\dot{E}$)	L_{1400} (mJy kpc^2)	Reference
J1846−0258	Kes 75	323	2.9	36.9	21	X	175	8	…	1
J0205+6449	3C 58	65	2.9	37.4	3.2	(X)R	0.4	0.007	~0.5	2
B0531+21	Crab	33	3.0	38.7	2	RX	29	1	56	3
B1509−58	MSH 15-52	150	3.2	37.3	5	(X)R	8	1.7	35	4
J1119−6127	G292.2−0.5	407	3.2	36.4	~6	RX	0.02	0.1	~29	5
J1811−1925	G11.2−0.3	64	3.2	36.8	5	X	5	0.6	…	6
J1124−5916	G292.0+1.8	135	3.5	37.1	>6	(R)X	0.2	0.02	≳3	7
J1930+1852	G54.1+0.3	136	3.5	37.1	~5	(R)X	1.7	0.3	~2	8
J1357−6429	*G309.8−2.6?*	*166*	*3.9*	*36.5*	*~2.5*	R	?	?	*~3*	9
B1610−50	…	231	3.9	36.2	~7.8	R	<0.7	<0.7	~150	10
J1617−5055	…	69	3.9	37.2	~6.7	XR	…	1	~22	11
J1734−3333	…	1169	3.9	34.7	~7.4	R	?	?	~27	12

Notes.—Anomalous X-ray pulsars and soft γ-ray repeaters are not included in this list. For definiteness, we also do not include a few pulsars that may well have $\tau < 10$ kyr but for which $\tau_c \gtrsim 10$ kyr, such as the Vela pulsar and PSR J2229+6114 (Halpern et al. 2001).

[a] For B0531+21, J0205+6449, and J1811−1925, historical ages are given assuming associations with SN 1054, SN 1181, and SN 386, respectively (Stephenson & Green 2002); for other pulsars, we list the characteristic age, $\tau_c \equiv P/2\dot{P}$.

[b] Spin-down luminosity, $\dot{E} \equiv 4\pi^2 I\dot{P}/P^3$, where P is the pulsar period and $I \equiv 10^{45}$ g cm^2.

[c] Pulsations detected in X-rays (X) or radio (R). Discovery wave band is listed first, and directed searches are denoted by parentheses.

[d] X-ray luminosities are all given in the 2–10 keV band and assume isotropic emission.

References.—In each given reference, further references can be found to the X-ray observations and distance estimates, where appropriate. (1) Helfand et al. (2003); (2) Slane et al. (2004); (3) Weisskopf et al. (2000); (4) Gaensler et al. (2002); (5) Gonzalez & Safi-Harb (2003); (6) Roberts et al. (2003); (7) Hughes et al. (2003); (8) Camilo et al. (2002a); (9) this work; (10) Pivovaroff et al. (2000); (11) Kaspi et al. (1998); (12) Morris et al. (2002).

in the 2.4 GHz continuum survey of Duncan et al. (1995), with two SNR candidates proposed by Duncan et al. (1997) indicated. It is not clear what, if any, is the relationship between both SNR candidates, or of either one with a much larger superposed shell SNR candidate, G310.5−3.5. Also, no spectral, distance, or age information is available for these candidates. The G309.8−2.6 SNR candidate appears at this resolution to be about 30′ in length with a relatively bright resolved "core" to the southwest. In turn, PSR J1357−6429 is located, at least in projection, slightly to the east of this core but coincident with emission from the SNR candidate. Apart from PSR J1357−6429, there are seven other known pulsars located in the area of the figure, all old, with 0.5 Myr $< \tau_c <$ 70 Myr.

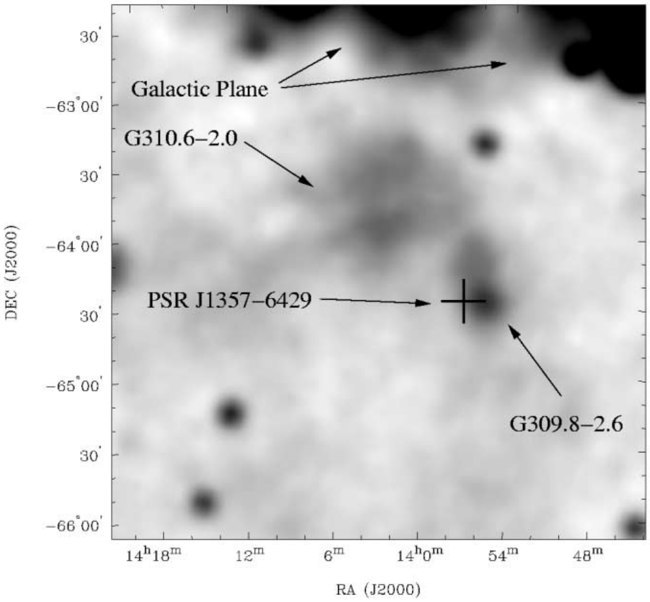

Fig. 2.—The 2.4 GHz image of the Galactic plane in the vicinity of PSR J1357−6429, using data from the Parkes continuum survey of Duncan et al. (1995), at a spatial resolution of 10′. The gray scale is linear and ranges between −0.15 and +1.3 Jy beam^{-1}. The two SNR candidates in this region proposed by Duncan et al. (1997) are indicated, while the position of the pulsar is marked by a cross (the size of the cross is much larger than the positional uncertainty of the pulsar).

4. DISCUSSION

PSR J1357−6429, with $\tau_c = 7300$ yr, is among the youngest pulsars known in the Galaxy. It is also the second youngest pulsar discovered in the Parkes multibeam survey, after PSR J1119−6127 with $\tau_c = 1600$ yr (Camilo et al. 2000). The pulsar is located near the SNR candidate G309.8−2.6. While all apparently younger pulsars are associated with either a PWN or an SNR, three slightly older pulsars are not obviously associated with either such object (Table 2). Further work is therefore needed in order to investigate the nature of G309.8−2.6 and also to determine whether it is in fact associated with the pulsar.

Being a young and energetic pulsar located at apparently only ~3 kpc, one would expect substantial X-ray emission to be detectable from PSR J1357−6429. As shown in Table 2, this is the case for all younger pulsars (interestingly, only the Crab pulsar among these is a known optical emitter, and only the Crab and PSR B1509−58 are known γ-ray emitters). A check of the HEASARC archives reveals no useful data to address this question, and X-ray observations of this source will have to be carried out. Also, there is no known EGRET γ-ray source coincident with this relatively energetic and nearby pulsar (Hartman et al. 1999), but PSR J1357−6429 is likely to be a good target for the future *GLAST* mission.

The large value of $\ddot{\nu}$ (and hence apparent n) implied by the increasing $\dot{\nu}$ (Fig. 1) possibly results from decay after previous (unseen) glitches (Johnston & Galloway 1999; Wang et al. 2000). However, it is notable that there is no discernible jump in $\ddot{\nu}$ at the time of the observed glitch. In most cases, following a large glitch, a portion of the jump in ν and $\dot{\nu}$ decays with a timescale that ranges from a few days (for the Crab pulsar) to many months (in the Vela pulsar). This results in a jump in $\ddot{\nu}$ at the time of the glitch. The absence of this for the present glitch suggests either that the decay timescale is much longer than our data span or that different glitches in this pulsar have different characteristics.

The radio luminosity of PSR J1357−6429 is $L_{1400} \equiv S_{1400} d^2 \sim 3$ mJy kpc^2, where S_{1400} is the flux density in the 1400 MHz band. This is a rather low value: for the 10 radio pulsars in Table 2, the median $L_{1400} \sim 25$ mJy kpc^2. However, it is in keeping with the realization that the very youngest pulsars ($\tau \lesssim 10$ kyr) are not obviously more luminous than slightly older pulsars (the median luminosity for pulsars with $\tau_c < 10^5$ yr is $L_{1400} \sim 30$ mJy kpc^2; Camilo 2004) or than middle-aged pulsars (e.g., Camilo et al. 2002b).

As we now show, the discovery of a low-luminosity pulsar such as PSR J1357−6429 contributes greatly toward the estimated birthrate of very young pulsars. To do this, we make use of the pulsars listed in Table 2 that were detected in the Parkes multibeam survey: B1509−58, J1119−6127, J1357−6429, B1610−50, and J1734−3333. For each pulsar, we carried out a Monte Carlo simulation to correct for the volume of the Galaxy probed by the multibeam survey, using the $V/V_{\max}$-style technique to estimate the total number of similar objects beaming toward Earth (for details, see, e.g., Lorimer et al. 1993 and references therein). Using the most recent estimates of the Galactic pulsar distribution in these simulations (Lorimer 2004), we find that the total number of such pulsars with $\tau_c < 10$ kyr is 107 ± 95. Taking into account the correction due to the unknown "beaming fraction" f, the implied birthrate of this population is $\Sigma = (1.1 \pm 1.0)/f$ per century (where $f \approx 0.5$; e.g., Frail & Moffett 1993). While having a large uncertainty (reflecting the inclusion of PSR J1357−6429, which accounts for 90% of the $V/V_{\max}$ correction so that it dominates the calculation; more generally, we may not know enough about the low end of the radio luminosity distribution), this birthrate is comparable to those obtained using much larger (and on average much older) samples (e.g., Lorimer et al. 1993; Lyne et al. 1998).

Despite the poorly known pulsar birthrate and beaming fraction, it appears unlikely that more than ≈100 Galactic pulsars with $\tau_c < 10$ kyr are beaming toward us, since the estimated core-collapse SN rate in our Galaxy (while also having significant uncertainties) must account also for other branches of neutron star production (see, e.g., Brazier & Johnston 1998; Gaensler et al. 1999, 2000 for discussions of birthrates of other types of neutron stars). In this case, the 11 pulsars listed in Table 2 located on the "near side" of the Galaxy (all but PSR J1846−0258) could represent about one-quarter of all such young pulsars from which we may ever detect pulsations. Alternatively, the discovery of many more would have significant implications for some of the assumptions underlying these estimates. Nine of the 12 pulsars listed in Table 2 have been discovered in the past 7 yr, in both directed and undirected searches, and at radio wavelengths as well as in X-rays, methods that suffer from significantly different selection effects. In view of the above discussion, it is important to continue with such searches, employing diverse methods.

Young pulsars are rare, and young nearby ones are rarer still. If PSR J1357−6429 is indeed located at $d \lesssim 3$ kpc, with a visual extinction $A_V \lesssim 6$, and with a probable real age of 5–15 kyr, it is well possible that its birth event provided a spectacular sight to some of our recent prehistorical ancestors. Of greater relevance for us, if not quite as spectacularly, future study of this very young and nearby pulsar and any possible PWN/SNR companion may contribute one more significant piece toward understanding young neutron stars and their environments.

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