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 \( 3.1 \times 10^{38} \) erg 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 \( \sim 2.5 \) 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 \( \sim 100 \) 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 (\( |b| < 5^\circ \); \( 260^\circ < l < 50^\circ \)). 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, \( \tau \equiv P/2\dot{P} = 7300 \) 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 \( \approx 10 \) 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 \( \sim 500 \) 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

8 See http://www.atnf.csiro.au/research/pulsar/tempo.
jump in spin parameters at the glitch epoch. We emphasize that the
value of \( \dot{\nu} \) is not deterministic (see also Fig. 1). It yields
an apparent braking index of rotation \( n = \dot{\nu}/\ddot{\nu} \approx 40 \) (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, 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, 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.

Fig. 1.—Spin history of PSR J1357–6429. The frequency (\( \nu \)) evolution
is shown in panels a and b, the latter with an expanded scale after removal of \( \nu \) 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).

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 \( \tau = 2\tau_n[1 - (\nu_0\nu_n^{-1})]/(n - 1) \), where \( \nu_0 \) is the initial rotation frequency of the neutron star. However, we do not know the actual braking index of the pulsar. However, if it lies in the range \( 2 \leq n \leq 3 \), as is the case for all four pulsars with age measured via phase-coherent timing (see Camilo et al. 2000 and references therein), then the real age is still \( \tau \approx 15 \) kyr and may be less than 10 kyr, depending on the actual values of \( n \) and \( \nu_0 \). 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 \( \sim \) 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 \( d \approx 4 \) 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 \( \tau \approx 10 \) 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
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 < τ < 70 Myr.

4. Discussion

PSR J1357−6429, with τ < 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 τ = 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 this is the case for all younger pulsars (interestingly, 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 ν (and hence apparent n) implied by the increasing ν (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 ν at the time of the observed glitch. In most cases, following a large glitch, a portion of the jump in ν 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 ν at the time of the glitch. The absence of this for the present glitch suggests

![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).](image-url)
either that the decay timescale is much longer than our data span or that different glitches in this pulsar with \( \tau < 10 \) 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 wave-lengths 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 \( A_V \approx 6 \), 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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