

PSR J0609+2130: a disrupted binary pulsar?

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ABSTRACT

We report the discovery and initial timing observations of a 55.7-ms pulsar, J0609+2130, found during a 430-MHz drift-scan survey with the Arecibo radio telescope. With a spin-down rate of $3.1 \times 10^{-19} \text{ s s}^{-1}$ and an inferred surface dipole magnetic field of only $4.2 \times 10^9 \text{ G}$, J0609+2130 has very similar spin parameters to the isolated pulsar J2235+1506 found by Camilo, Nice & Taylor. While the origin of these weakly magnetized isolated neutron stars is not fully understood, one intriguing possibility is that they are the remains of high-mass X-ray binary systems which were disrupted by the supernova explosion of the secondary star.

Key words: pulsars: general – pulsars: individual: J0609+2130.

1 INTRODUCTION

Radio pulsars are categorized as either ‘normal’ or ‘recycled’ objects. Normal pulsars are observationally more numerous and are predominantly young isolated objects with spin periods in the range $30 \text{ ms} < P < 8 \text{ s}$, strong inferred surface dipole magnetic field strengths ($B \sim 10^{12} \text{ G}$) and characteristic ages in the range $10^3 < \tau < 10^7 \text{ yr}$. Recycled pulsars have shorter spin periods ($1.5 \text{ ms} < P < 60 \text{ ms}$), weaker magnetic fields ($10^8 < B < 10^9 \text{ G}$), larger ages ($10^8 < \tau < 10^{10} \text{ yr}$) and are usually members of binary systems with either white dwarf or neutron star companions.

The normal pulsars are thought to be born in supernovae and spin down owing to magnetic dipole braking (see e.g. Gunn & Ostriker 1970). The favoured theory for the origin of recycled pulsars involves an old neutron star that is spun up (recycled) through the accretion of matter from a binary companion which overflows its Roche lobe (Bisnovaty-Kogan & Komberg 1974). During the spin-up phase, the system is expected to be visible as an X-ray binary. The duration of the X-ray phase and amount of spin up depends upon the mass of the companion star. For those companions massive enough to explode as a supernova, the X-ray lifetime is relatively short (10^{6-7} yr) and the most likely outcome is the disruption of the binary. Those systems fortunate enough to survive the explosion are the double neutron star (hereafter DNS) binaries (e.g. the original binary pulsar B1913+16). For less massive companions,

where the period of spin up is longer (10^8 yr), the subsequent collapse leaves a white dwarf star in orbit around a rapidly spinning millisecond pulsar. For a detailed review of these evolutionary scenarios, see Bhattacharya & van den Heuvel (1991) and references therein.

In order to understand the population of recycled pulsars in detail, a statistically significant sample is required. Because of their short spin periods and, often, binary orbits, detecting these elusive objects is a computationally intensive process requiring state-of-the-art data acquisition systems, significant data storage and computational power for post processing. In 1994 the Penn State Pulsar Machine (PSPM), a new analogue filterbank spectrometer (Cadwell 1997), was installed at the 305-m Arecibo telescope and has been in regular use as a pulsar search and timing instrument ever since. In 2002 March, we began using part of a high-speed computer cluster to process various sets of PSPM data taken during the latter stages of the Arecibo upgrade (1996–8). To date, we have discovered a dozen new pulsars and re-detected over 40 previously known ones. Preliminary details of the search were given by McLaughlin et al. (2003).

Here we report on an isolated 55.7-ms pulsar J0609+2130, one of the first new discoveries from our searches. While the spin parameters of the new pulsar are similar to other recycled pulsars, the lack of a binary companion poses interesting questions as to its origin. The layout of the rest of this paper is as follows: in Section 2 we briefly describe the survey observations, data acquisition system and analysis pipelines. The results of the analysis and subsequent timing observations of J0609+2130 are given in Section 3. Finally,

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in Section 4, we discuss the new pulsar's properties in the context of its likely origin and evolution.

2 SURVEY OBSERVATIONS AND ANALYSIS

The data presented here were taken with the Arecibo radio telescope during a 9.5-h maintenance period in 1998 October when upgrade operations required that the telescope was parked at 35:7 azimuth. The 430-MHz line-feed system, traditionally used for pulsar observations, was not available for use on this occasion. We therefore took advantage of the newly commissioned 430-MHz receiver in the Gregorian dome which was in a fixed position at 3:9 from the zenith. Although the 430-MHz Gregorian receiver¹ illuminates less of the dish than the line-feed so that the forward gain is lower (11 K Jy⁻¹ cf. 18 K Jy⁻¹ for the line feed), the lower system temperature (45 K cf. 120 K) and reduced levels of interference make it a very attractive receiver for pulsar searching. In this setup, sources at declination δ drift through the 11-arcmin primary beam in $\sim 44/\cos \delta$ s. The total area covered was ~ 22 deg² along an 11-arcmin slice through the Galactic anti-centre in the right ascension range $1.5^{\text{h}} < \alpha < 10^{\text{h}}$ centred at $\delta \simeq 21:5$.

The incoming signals from the telescope were passed to the PSPM which summed the two independent polarizations before 4-bit sampling the band into 128×60 -kHz channels every 80 μ s. For this choice of sampling interval, a 2¹⁹-pt Fourier transform is well matched to the 44-s transit time of sources through the 430-MHz beam. The resulting data were then written directly to magnetic tape for offline analysis.

Searches for periodic and transient radio signals in the data were carried out using COBRA, a 180-processor Beowulf cluster at Jodrell Bank Observatory. Deferring a more complete discussion for a future paper, we now briefly outline the main procedures. To correct for the dispersive effects of the interstellar medium, the raw PSPM data were dedispersed at 392 different trial dispersion measures (DMs) in the range $0 \leq \text{DM} \leq 491.2$ cm⁻³ pc using freely available analysis tools (Lorimer 2001). The resulting dedispersed time series were then passed to two different analysis pipelines. In the first, the data were Fourier-transformed and the resulting amplitude spectra were searched for significant features indicating the presence of a periodic signal. To increase the sensitivity to narrow duty cycle pulses, spectra summing 2, 4, 8 and 16 harmonics were also searched. Candidates with signal-to-noise ratios (S/N) above 8 were then analysed in the time and radio frequency domain to produce diagnostic plots which were saved for later visual inspection. Further details can be found in Lorimer et al. (2000).

In the second analysis pipeline, the dedispersed data were searched in the time domain for pulses with S/N > 5 using software developed by Cordes & McLaughlin (2003). This search was aimed at finding individual and giant pulses from some pulsars where the periodic signal may be below the threshold of the Fourier analysis (see e.g. Nice 1999). To maximize sensitivity over a variety of pulse widths, each time series was smoothed by up to 64 adjacent samples.

Given the measured system equivalent flux density of the 430-MHz Gregorian receiver (3.3 Jy), we estimate the sensitivity of the Fourier analysis to be ~ 0.5 mJy to long-period pulsars observed away from the Galactic plane. For millisecond pulsars, with typical periods of 5 ms and pulse duty cycles of order 60 per cent, we estimate the sensitivity to be closer to 3 mJy. The detection threshold

of the single-pulse search is about 0.5 Jy to the narrowest pulses. Full details of the search sensitivity will be presented elsewhere.

3 RESULTS AND TIMING OBSERVATIONS

Two pulsar-like signals were detected in the periodicity search. One of these was the 33-ms Crab pulsar, B0531+21 (also seen in the single-pulse analysis) detected in several adjacent beams with S/N ~ 18 . The remaining candidate, a 55.7-ms signal with DM ~ 40 and S/N ~ 9 , was re-observed and confirmed as the new pulsar J0609+2130 in 2002 April. Only one other previously known pulsar, B0525+21, lies within the region covered by this search. This was not detected in either the periodicity or the single-pulse search. A closer scrutiny of the raw search data revealed no detectable signal. Since the data were not obviously affected by radio-frequency interference, two possible effects are responsible for the non-detection: either (a) since this pulsar is known to null for approximately 25 per cent of the time (Biggs 1990) it is quite likely that the survey observations caught this pulsar in a null state; or (b) the flux density of the pulsar was significantly reduced by diffractive interstellar scintillation. Given the normally high mean flux density of this pulsar (7 mJy at 408 MHz; Lorimer et al. 1995), nulling seems the most likely explanation for the non-detection.

To determine the detailed spin and astrometric parameters of J0609+2130, we have been carrying out regular 430-MHz timing observations since 2002 June. These observations use the PSPM in timing mode, where the incoming signals are folded modulo the period predicted from an ephemeris initially derived from the confirmation observation. In timing mode, folded 1024-bin pulse profiles for each of the 128 frequency channels of the PSPM are written to disc every 180 s. We initially collected at least three of these 180-s observations per epoch in order to enable high-precision estimates of the pulse period. The timing analysis proceeded by forming the dedispersed profile across the band of the PSPM for each 180-s observation and estimating the pulse phase by cross correlating each profile with a high S/N template using procedures identical to those described in detail by Lorimer, Camilo & Xilouris (2002).

The topocentric pulse arrival times were fitted to a simple timing model involving spin and astrometric parameters using the TEMPO² software package. Once a preliminary phase-connected timing solution was obtained, a better template was formed by phase-aligning the pulse profiles according to the best-fitting model. The final template profile is shown in Fig. 1. As part of this refinement procedure, individual 180-s observations on a given day were phase aligned and averaged together to produce one pulse arrival time per observing session. The estimate of DM from the search analysis was improved by analysing PSPM observations with the 327-MHz and 610-MHz Gregorian receivers on February 17, 2003, and using TEMPO to fit for the dispersion delay between the frequency bands. The best-fitting timing model for 30 arrival times spanning the MJD range 52427–52796 results in featureless timing model residuals with a post-fit RMS of 44 μ s. The resulting parameters are given in Table 1.

4 DISCUSSION

4.1 Basic properties of J0609+2130

PSR J0609+2130 is a very weak radio source. Using the calibration procedures described by Lorimer et al. (2002), we find the mean

¹ see <http://www.naic.edu/~astro/RXstatus> for full details of currently available Arecibo receiving systems.

² <http://pulsar.princeton.edu/tempo>

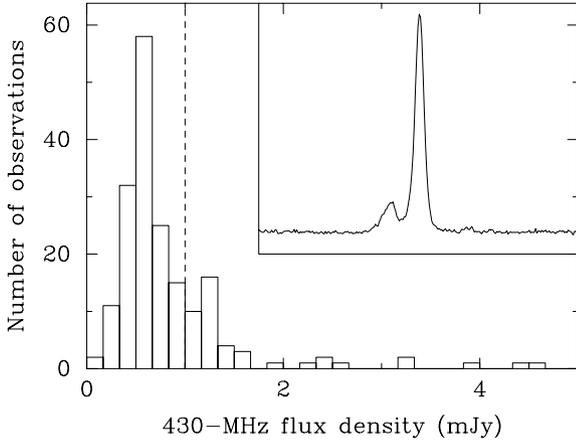


Figure 1. Distribution of 430-MHz flux densities for PSR J0609+2130 based on individual 180-s observations. The dashed line shows the detection threshold for this pulsar in our original search-mode observation. Inset: integrated 430-MHz profile showing 360° of rotational phase. The profile was produced by phase-aligning and summing all the 430-MHz detections. The equivalent integration time and effective time resolution are 9.8 h and $256 \mu\text{s}$ respectively.

Table 1. Observed and derived parameters for PSR J0609+2130.

Parameter	Value
Right ascension (h:m:s) (J2000)	06:09:58.883(1)
Declination (deg:m:s) (J2000)	21:30:02(1)
Spin period, P (ms)	55.6980139253(2)
Epoch of period (MJD)	52575.0
Period derivative, $\dot{P} \times 10^{-19} \text{ s s}^{-1}$	3.1(6)
Dispersion measure, DM ($\text{cm}^{-3} \text{ pc}$)	38.77(5)
Mean flux density at 430 MHz, S_{430} (mJy)	0.8(1)
Galactic longitude, l (deg)	189.192
Galactic latitude, b (deg)	1.04
Characteristic age, τ (Gyr)	2.8
Magnetic field strength, B (10^9 G)	4.2
Distance, d (kpc)	1.2
430-MHz radio luminosity, L_{430} (mJy kpc 2)	~ 1.15

The numbers in parentheses represent 1σ uncertainties in the least significant digit quoted and are twice the formal fit estimates from TEMPO. The characteristic age and magnetic field are calculated as described in Section 4. The distance is derived using the Galactic electron density model of Cordes & Lazio (2003).

430-MHz flux density of the pulsar S_{430} to be only 0.8 ± 0.1 mJy at 430 MHz. Given the distance estimate $d \simeq 1.2$ kpc from the new electron density model of Cordes & Lazio (2003), the 430-MHz radio luminosity $L = Sd^2 \sim 1.15$ mJy kpc 2 . Only 10 out of the 612 pulsars currently in the online catalogue³ with measured luminosities are fainter sources than PSR J0609+2130.

The flux density of the pulsar is clearly affected by interstellar scintillation. We observe variations between 0.1 and 5 mJy as shown in Fig. 1. Indeed, for about 75 per cent of the observations we have taken, the flux density is below our nominal survey threshold of about 1 mJy for this pulsar. Although our observations at other frequencies are not yet numerous enough to characterize the radio spectrum of J0609+2130 with any certainty, our preliminary flux

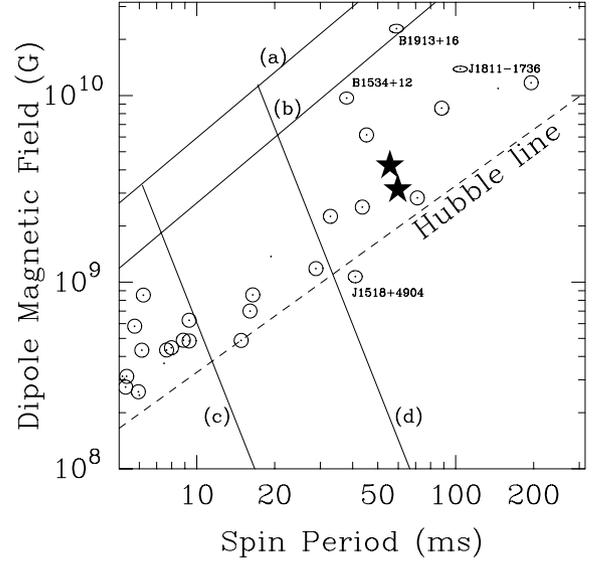


Figure 2. Part of the magnetic field versus period ($B - P$) diagram highlighting the unique positions of the solitary pulsars J0609+2130 and J2235+1506 (starred symbols). Pulsars with surrounding ellipses are members of binary systems, with the eccentricity of the ellipse representing the orbital eccentricity. Known DNS binary systems are labelled appropriately. The ‘Hubble line’ is the locus of points of constant characteristic age equal to a Hubble time (assumed to be 15 Gyr). The four lines show limiting spin-up values for Alfvén accretion at the Eddington limit and one fifth of Eddington (labelled ‘a’ and ‘b’ respectively), and terminated accretion after a donor star life time 10^6 yr for the same accretion rates (labelled ‘c’ and ‘d’). Pulsars in globular clusters and the Magellanic clouds have been excluded.

estimate of 2 mJy at 327-MHz implies that it is a steep-spectrum source that is most readily detectable in low-frequency surveys.

Our timing measurements of PSR J0609+2130 reveal a period derivative $\dot{P} = 3 \times 10^{-19}$. PSR J0609+2130 therefore appears to be an old neutron star with characteristic age $\tau = P/(2\dot{P}) = 2.8$ Gyr and a relatively weak surface dipolar magnetic field $B = 3.2 \times 10^{19} \sqrt{P\dot{P}} = 4.2 \times 10^9 \text{ G}$. Of all the sources in the current pulsar catalogue, the one which has properties most similar to J0609+2130 is PSR J2235+1506, a solitary 57.9-ms pulsar with $\dot{P} = 1.7 \times 10^{-19}$ (Camilo, Nice & Taylor 1993, 1996). The positions of both these pulsars on the $B - P$ diagram are shown in Fig. 2. As can be seen, J0609+2130 and J2235+1506 are the only two solitary pulsars in this part of the diagram. We shall return to the positions in the $B - P$ plane later in the discussion.

4.2 The Galactic population and evolution of weakly magnetized solitary pulsars

Based on the close proximity and low radio luminosities of J0609+2130 and J2235+1506 we expect pulsars like them to be quite common in the Galaxy. Indeed, Kalogera & Lorimer (2000) estimated the Galactic population of pulsars like J2235+1506 to be $\sim 5000/f$, where f is the fraction of 4π sr covered by the radio beam. For a beaming fraction of 30 per cent (i.e. $f = 0.3$) the Galactic population of these objects is likely to be of order 15 000.

What is the origin of weakly magnetized isolated pulsars like J0609+2130 and J2235+1506? One possibility is that they are simply part of the same population as the normal pulsars. To investigate this idea quantitatively, we can take the best-fitting

³ <http://www.atnf.csiro.au/research/pulsar/psrcat>

initial magnetic field distribution from the recent population study of isolated pulsars by Arzoumanian, Chernoff & Cordes (2002). For their distribution, only about one in the expected Galactic population of 10^9 neutron stars is born with $B < 10^{10}$ G, clearly inconsistent with the population estimates made above. Unless there is a weak-field component to the neutron star magnetic field distribution that has been overlooked by population studies so far, a more efficient means of forming these weakly magnetized neutron stars is required.

A pulsar born with a stronger magnetic field could, in principle, evolve to resemble PSR J0609+2130 through long-term decay of the magnetic field. While the existence of field decay for the pulsar population at large remains controversial (see e.g. Bhattacharya et al. 1992) available evidence suggests that, for objects comparable in age and magnetic-field strength to J0609+2130, any decay must act on extremely long time-scales. Where such pulsars are found in binary systems, studies of their white-dwarf companions provide an independent age estimate through cooling models, affirming the long-lived nature of the pulsars and constraining the existence of field decay (Kulkarni 1986). Of course, J0609+2130 is an isolated pulsar, but it seems unlikely that non-binarity would somehow encourage rapid field decay.

Camilo et al. (1993) suggested that J2235+1506 might be the remains of a high-mass binary system that disrupted at the time of the second supernova explosion. In this scenario, PSRs J0609+2130 and J2235+1506 are the first-born neutron stars in their respective binaries and initially spin down as regular neutron stars. During Roche-lobe overflow from the subsequently evolved secondary star, mass accretion reduces the magnetic field (see e.g. Romani 1990), and also spins up the neutron star in the process. If the secondary is sufficiently massive to undergo a supernova explosion, the most likely outcome is disruption of the binary, releasing a newly-born neutron star and a recycled pulsar. Those binary systems more likely to survive this explosion as DNS binaries are the tightly-bound systems with short orbital periods. The wider binaries, which are much less likely to survive the explosion, release recycled pulsars with spin properties akin to J0609+2130 and J2235+1506 into the Galactic field. We hereafter refer to these as ‘disrupted recycled pulsars’ (DRPs).

Using this evolutionary scenario for DRPs as a working hypothesis, we now return to the $B - P$ diagram in Fig. 2 to investigate the post-accretion spin periods of DRPs after the accretion phase. In their analysis of DNS binaries, Arzoumanian, Cordes & Wasserman (1999, hereafter ACW) discuss two equilibrium spin period relations for the spin-up of a neutron star in a binary system. The first of these is the familiar limit for spherical accretion of matter in which the limiting spin period is set by the corresponding Keplerian orbital period at the so-called Alfvén radius (see e.g. Ghosh & Lamb 1992). On the $B - P$ plane, this translates to a relationship of the form $B \propto P^{5/3}$. The constant of proportionality in this expression depends on a number of factors such as the mass accretion rate, the radius and moment of inertia of the neutron star and the opacity of the accreting material. The uncertainties in these parameters result in a family of $B \propto P^{5/3}$ curves. Two such curves, assuming accretion at the Eddington rate and at one-fifth of this value, are plotted on Fig. 2 using the relationship quoted by ACW. For any pulsar, in the absence of magnetic field decay, we can estimate the spin period at the end of the accretion phase by tracing a horizontal line from the current position on Fig. 2 to the spin-up line. Under these assumptions, we infer that the initial spin period of J0609+2130 and J2235+1506 would have been in the range 10–20 ms.

ACW pointed out that, for high-mass binary systems, the above picture is oversimplified since the lifetime of the donor star will be much less than the accretion time-scale at which the Alfvén limit is reached. They show that this condition produces a second family of limiting period curves which, on the $B - P$ plane, take the form $B \propto P^{-7/2}$. As noted by ACW, these curves are much more sensitive to uncertainties in the accretion parameters. In Fig. 2 we plot two such spin-up lines, again assuming accretion at the Eddington rate and one-fifth of this limit. It is clear that, for sub-Eddington accretion, the initial spin period of these DRPs would be much longer, perhaps very similar to their currently observed spin periods.

As noted by ACW, since pulsar characteristic ages $\tau = P/(2\dot{P})$ assume a negligible post-accretion spin period, one consequence of these accretion scenarios is that DNS binaries are younger objects than their characteristic ages suggest. If DRPs are formed by a similar process, the same applies to them. For example, a more likely ‘post-spinup’ age for J0609+2130 based on a limiting spin period of 40 ms would be about half its characteristic age (i.e. about 1.5 Gyr).

4.3 Testing the DRP hypothesis

Is the DRP hypothesis consistent with the observations? One parameter that can be confronted by both theory and observation is the ‘survival probability’ of the binary system, hereafter η , defined as the fraction of binary systems that remain bound after the second supernova explosion. Numerous authors have followed the orbital evolution of a wide variety of binary systems containing neutron stars using detailed Monte Carlo simulations (see e.g. Lipunov & Prokhorov 1984; Dewey & Cordes 1987; Fryer & Kalogera 1997). We use the relatively up-to-date simulations of Portegies Zwart & Yungelson (1998) who include a Maxwellian kick velocity distribution with a mean of 415 km s^{-1} in their simulations. From the results presented in table 1 of their paper, for this model, we infer $\eta \sim 4$ per cent. Based upon this low survival probability, we therefore expect DRPs to be much more common in the Galaxy than the DNS binaries.

To estimate η from an observational perspective, we note that the expected spin parameters of the recycled pulsar we observe in a DNS binary are the same as those of the putative DRPs. We can therefore reasonably expect the pulsars in DNS binaries to have the same radio lifetimes as the DRPs. Hence, if N_{DNS} and N_{DRP} are the total numbers of DNS binaries and DRPs in the Galaxy, it follows that

$$\eta = \frac{N_{\text{DNS}}}{N_{\text{DNS}} + N_{\text{DRP}}}.$$

Using the results of a recent population study of DNS binaries by Kim, Kalogera & Lorimer (2003), we take N_{DNS} to be ~ 1500 (a factor of 2 higher than quoted by Kim et al. 2003, to crudely account for the population of DNS binaries that do not coalesce in a Hubble time). Using the above estimate of $N_{\text{DRP}} = 15000$, we find $\eta \simeq 1500/(15000 + 1500) = 9$ per cent.

One outstanding issue is the observed numbers of DRPs. Given the above estimate for η , we would expect to see roughly 10 DRPs for each DNS binary. So far, however, we have identified only two DRPs: J0609+2130 and J2235+1506, compared to four DNS binaries in Fig. 2. Three main possibilities which might explain this apparently significant deficit of DRPs are as follows.

(i) DRPs are present in the observed sample, but are hard to identify since they have no binary companion. Although there are

perhaps a further four DRP-like pulsars known (see table 1 of Kalogera & Lorimer 2000), a more thorough analysis of the sample would be worthwhile.

(ii) The neutron star kick velocity distribution could be lower than assumed in the population synthesis. This would lead to an increase in η and reduce the discrepancy. A population synthesis dedicated to this question would certainly be useful.

(iii) The above DRP population estimates are somewhat crude and are based currently on J2235+1506 which is a nearby, low-luminosity object. A revision of these estimates to better account for small-number statistics is strongly recommended.

In summary, while it seems currently plausible that J0609+2130 and J2235+1506 are examples of disrupted X-ray binary systems, there are a number of open issues linking the two populations. Careful population studies to properly identify and estimate the DRP population and binary population syntheses to predict the survival rate are both strongly recommended. Further observational input should come both in the substantial numbers of pulsars now being found in the Parkes Multibeam survey (Manchester et al. 2001), and also proper motion measurements. For J2235+1506, the implied transverse speed is $V_t = 100 \pm 40 \text{ km s}^{-1}$ (Camilo et al. 1996). If J0609+2130 has a similar proper motion, it should be detectable in our ongoing Arecibo timing observations by early 2005.

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