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# DISCOVERY OF THREE BINARY MILLISECOND PULSARS

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## ABSTRACT

We report the discovery of three binary millisecond pulsars in circular orbits with low-mass companions from a continuing survey of the southern sky with the Parkes radio telescope. The three pulsars, PSR J0034−0534, PSR J1045−4509, and PSR J2145−0750 have pulse periods of 1.87, 7.47, and 16.05 ms and orbital periods of 1.6, 4.1, and 6.8 days, respectively. PSR J2145−0750 has a spin-down age of $\gtrsim 12$ Gyr, which raises interesting questions about its progenitor and initial pulse period. The properties of the growing class of radio pulsars with low-mass companions are discussed, and we suggest that their velocities, and a tendency for the short-period pulsars to have small orbital periods, are consistent with their formation from Type II supernova explosions.

*Subject headings:* pulsars: individual (PSR J0034−0534, PSR J1045−4509, PSR J2145−0750) — pulsars: formation

## 1. INTRODUCTION

Before the early 1980s, pulsar surveys were insensitive to pulsars with periods much less than 100 ms, mainly because they sampled the incoming data only at intervals $\gtrsim 20$ ms. The discovery of the millisecond pulsar PSR B1937+21 by Backer et al. (1982) unveiled a new class of radio pulsars, the so-called millisecond pulsars. This new class possessed not only short rotation periods but also much smaller period derivatives, indicative of magnetic field strengths three or four orders of magnitude below those of the "normal" population.

Early surveys for millisecond pulsars concentrated on the Galactic plane and on globular clusters. The globular cluster surveys were very successful, discovering more than 20 millisecond pulsars. These pulsars have provided new insights into binary star and globular cluster evolution, but are less useful for many applications of precision pulsar timing (e.g., Backer & Hellings 1986; Taylor & Weisberg 1989) because of the perturbing effects of the cluster gravitational field (Blandford, Romani, & Applegate 1987). Early surveys of the Galactic disk discovered two millisecond pulsars, PSR B1855+09 and PSR B1957+20 (Segelstein et al. 1986; Fruchter, Stinebring, & Taylor 1988). However, it was a survey by Wolszczan (1991) which discovered the millisecond pulsar PSR B1257+12 at a Galactic latitude of 75°, which first indicated that substantial numbers of these objects may be found at intermediate and high latitudes, a result predicted by modeling of the likely Galactic population (Johnston & Bailes 1991).

Here we report the discovery of three binary millisecond pulsars with the Parkes telescope in a survey of the southern sky. The very strong pulsar PSR J0437−4715, also discovered in this survey, has already been reported by Johnston et al. (1993). These pulsars, together with those recently reported by Nice, Taylor, & Fruchter (1993), Camilo, Nice, & Taylor (1993), and Foster, Wolszczan, & Camilo (1993), bring the total number of known disk millisecond pulsars to 14. Many of these are relatively close to the Sun and at high Galactic latitude, confirming that there is a substantial population of these objects associated with the Galactic disk.

## 2. OBSERVATIONS AND ANALYSIS

The three pulsars were discovered during the course of a survey of all the sky south of the equator, using the Parkes radio telescope. This survey began in 1991 May and at the time of discovery of the three pulsars was about 30% complete. Two orthogonal linearly polarized 32 MHz bands at a central observing frequency of 436 MHz are subdivided into 256 individual channels each 125 kHz wide. The signals from these channels are detected, added in polarization pairs and low-pass filtered. Sampling and one-bit digitization of the channels are performed every 300 $\mu$s and the resultant data written to an Exabyte tape. Away from the Galactic plane, the system temperature is 55 K, corresponding to a system equivalent flux density of $\sim 90$ Jy. Each point of the survey is observed for 157 s, giving a sensitivity of $\sim 3$ mJy to long-period pulsars with a duty cycle of 5% at the beam center.

Data analysis is carried out using networked computers at the Australia Telescope National Facility (10 SUN Sparcstations and a Convex C-2 computer) and at the University of Manchester, Jodrell Bank (two HP-720 workstations and five SUN Sparcstations). Each observation is reduced by dedispersing the data for values of dispersion measure up to the smaller of $42/\sin b$ and 740 pc cm$^{-3}$, where $b$ is the Galactic latitude. Fast Fourier transforms are then performed on the dedispersed data stream. To optimize sensitivity for the typical short pulse duty cycles, incoherently summed spectra for 2, 4, 8, and 16 harmonics are formed. These and the fundamental spectrum are then searched for significant spectral peaks.

The best pulsar suspects from this analysis are the reobserved, typically with an integration time of 600 s. For confirmed pulsars, pulse time-of-arrival measurements are then made using either the 76 m Lovell telescope at Jodrell Bank or

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the Parkes radio telescope at frequencies around 440, 660, and 1500 MHz. These timing observations are analyzed using standard techniques (Taylor & Weisberg 1989).

## 3. THREE BINARY MILLISECOND PULSARS

Parameters for the three millisecond pulsars, PSR J0034−0551, PSR J1045−4509, and PSR J2145−0750 are given in Table 1. Errors quoted are twice the formal rms errors from the least-squares fit. All three possess binary companions. The projected semimajor axis of the pulsar orbit and the orbital period determine the mass function for the binary system (Table 1). If we assume a pulsar mass $m_p = 1.4\ M_{\odot}$, then the minimum masses of the companions of PSR J0034−0534 and PSR J1045−4509 are both near 0.15 $M_{\odot}$, whereas the companion of PSR J2145−0750 is at least 0.43 $M_{\odot}$. It is almost certain that the companions are white dwarfs.

### 3.1. *PSR J0034−0534*

With its spin period of 1.877 ms, PSR J0034−0534 is the third fastest pulsar known. Its orbital period is also relatively short at 1.6 days. The characteristic age of the pulsar, usually taken as an upper limit to the actual age, is $\tau_c = P/(2\dot{P}) = 4.4$ Gyr, and the magnetic field at the neutron star surface, computed assuming a dipole field, is $B_0 \approx 3.2 \times 10^{19}\ (P\dot{P})^{1/2} \approx 1.1 \times 10^{8}$ G. This is the smallest magnetic field strength yet recorded for any pulsar. The equilibrium spin-up period (Bhattacharya & van den Heuvel 1991) for this pulsar is only 0.3 ms. It is very likely that the pulsar was born with a period greater than this minimum value. An independent estimate of the system's age, for example, from an optical identification of the companion and a white dwarf cooling model, would give a value for the initial spin period. Based on the dispersion measure, the distance model of Taylor & Cordes (1993) suggests that the pulsar is located between 0.75 and 1.3 kpc from the Sun. The pulse appears to have a broad, approximately Gaussian shape with a half-power width of ∼0.85 ms, or 45% of the period. There is no evidence for a strong interpulse similar to those seen in PSR B1937+21 or PSR B1957+20, the two pulsars with periods shorter than that of PSR J0034−0533.

### 3.2. *PSR J1045−4509*

PSR J1045−4509 has a pulse period of 7.45 ms and an orbital period of 4.09 days. It is 12° from the Galactic plane, and its dispersion measure, 58 $\mathrm{cm}^{-3}$ pc, places it at an estimated distance of 3.2 kpc. It is also quite strong, with a mean flux density at 400 MHz of ∼30 mJy. Its period and period derivative yield a characteristic age of 6.2 Gyr and a fairly typical magnetic field strength for a millisecond pulsar of $3.8 \times 10^{8}$ G. The energy loss rate of this pulsar ($\propto \dot{P}P^{-3}$) is low, and yet it is one of the more luminous millisecond pulsars known. It appears, therefore, that, as is the case for the normal pulsars, there is no simple dependence of the radio luminosity on period and magnetic field strength (Lorimer et al. 1993). As in the case of PSR J0034−0534, the radio pulse profile is relatively broad and featureless. The width at half-power is about 1.3 ms, or 18% of the period. There is no evidence for any interpulse, with a limit of about 5% of the main pulse amplitude.

### 3.3. *PSR J2145−0750*

The third pulsar, PSR J2145−0750, has a period of 16.1 ms, which is slower than that of any other disk millisecond pulsar. However, it clearly belongs in the same class, as it shares many other characteristics. The pulsar is in a 6.1 day circular binary orbit with a low-mass companion, probably a white dwarf. The upper limit on the period derivative indicates that the pulsar is not young. In fact, the characteristic age is at least 12 Gyr, greater than the age of the Galactic disk. It is virtually certain that this pulsar was born with a period greater than the minimum possible via mass accretion, $\lesssim 1$ ms. The large companion mass (minimum value 0.43 $M_{\odot}$) suggests that the progenitor of the white dwarf companion was also massive. This

TABLE 1

PARAMETERS OF THREE BINARY MILLISECOND PULSARS

| | PULSAR | | |
|---|---|---|---|
| PARAMETER | PSR J0034−0534 | PSR J1045−4509 | PSR J2145−0750 |
| R.A. (J2000) | $00^{h}34^{m}21\overset{s}{.}826$ (2) | $10^{h}45^{m}50\overset{s}{.}1964$ (7) | $21^{h}45^{m}50\overset{s}{.}440$ (5) |
| Decl. (J2000) | $-05°34'36\overset{''}{.}56$ (3) | $-45°09'54\overset{''}{.}216$ (7) | $-07°50'17\overset{''}{.}9$ (2) |
| Galactic longitude | $111\overset{\circ}{.}5$ | $280\overset{\circ}{.}9$ | $47\overset{\circ}{.}8$ |
| Galactic latitude | $-68\overset{\circ}{.}1$ | $12\overset{\circ}{.}3$ | $-42\overset{\circ}{.}1$ |
| Period (ms) | 1.87718185402 (2) | 7.47422410386 (2) | 16.0524236555 (2) |
| Period derivative ($\times 10^{-20}$) | 0.67 (6) | 1.9 (2) | <2 |
| Dispersion measure ($\mathrm{cm}^{-3}$ pc) | 13.763 (2) | 58.1649 (7) | 9.000 (1) |
| Epoch (MJD) | 48765.986 | 48821.0 | 48978.6573 |
| Orbital period (days) | 1.58928180 (3) | 4.0835291 (1) | 6.83890256 (8) |
| $a \sin i$ (light-s) | 1.437768 (5) | 3.015107 (9) | 10.16411 (1) |
| Eccentricity | $<1.0 \times 10^{-4}$ | 0.000019 (6) | 0.000021 (2) |
| Epoch of periastron (MJD) | 48765.599418 | 48822.379425 | 48925.425156 |
| Longitude of periastron | $0\overset{\circ}{.}0$ (assumed) | 230° (20) | 201° (5) |
| Flux density at 430 MHz (mJy) | 16 | 20 | 50 |
| Flux density at 1520 MHz (mJy) | <0.3 | 3 | 10 |
| Derived parameters: | | | |
| Characteristic age (Gyr) | 4.4 | 6.2 | >12.6 |
| Magnetic field ($10^{8}$ G) | 1.1 | 3.8 | <6 |
| Spectral index | $\lesssim -3$ | −1.5 | −1.3 |
| Mass function ($M_{\odot}$) | 0.00126 | 0.00176 | 0.0241 |
| Minimum companion mass ($M_{\odot}$) | 0.14 | 0.16 | 0.43 |
| Distance (kpc) | 1.0 | 3.2 | 0.5 |

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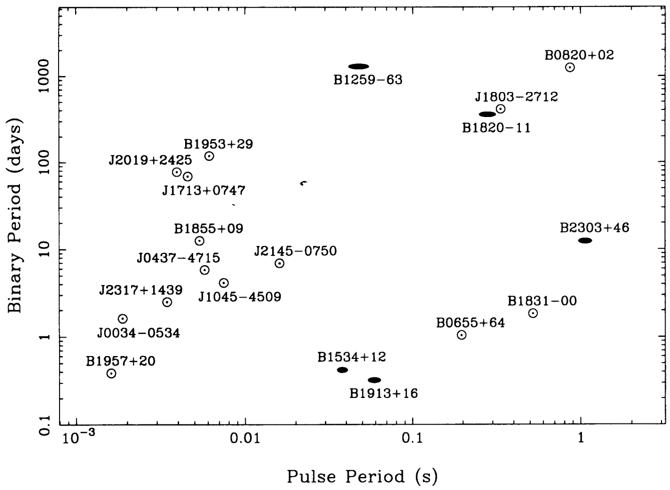

FIG. 1.—Distribution of binary pulsars in the spin period–orbital period plane. Pulsars in elliptical orbits are represented by an ellipse; the rest are in essentially circular orbits. There is a correlation emerging between the pulse period and the orbital period of those pulsars in circular orbits.

star would have a shorter evolutionary timescale, resulting in less time for spin-up, which might explain the large pulse period of the pulsar. The pulse profile is dominated by two components separated by 0.20 of the pulse period in phase, but there is also a weaker component leading the first of the stronger components by 0.18 in phase.

## 4. DISCUSSION

It is significant that none of the three pulsars shows any evidence for an interpulse, unlike many of those first discovered in the disk. Of the 11 millisecond pulsars reported in 47 Tucanae by Manchester et al. (1991), very few possessed interpulses, and this led Chen & Ruderman (1993) to postulate that millisecond pulsars in globular clusters were fundamentally different from those in the disk. The discovery of these three millisecond pulsars, and of PSR J0437−4715 (Johnston et al. 1993), PSR J1713+0747 (Foster et al. 1993), and PSR J2317−1439 (Camilo et al. 1993), none of which has an interpulse, must cast doubts upon the conclusions of Chen & Ruderman.

Now that a fairly large number of binary pulsars in the disk have been discovered, it is appropriate to consider their group properties. In Figure 1 we plot the spin periods of all of the disk binary pulsars against their orbital periods.[7] It is clear that there are several distinct classes of binary systems (cf. Bhattacharya & van den Heuvel 1991). The evolution of pulsars in elliptical orbits is largely noncontroversial. They have all descended from massive binary systems and are often referred to as the high-mass binary pulsars. Binary pulsars with circular orbits are believed to possess white dwarf companions, and their origin is more controversial. Strong tidal forces act to circularize their orbit while the companions were in the giant phase of their evolution. The main issues concern whether these low-mass binary pulsars (LMBPs) formed as the result of accretion-induced collapse of a white dwarf (van den Heuvel 1984) or as the result of a Type II supernova explosion (van den Heuvel 1983; Bailes, 1989; Verbunt 1990), and whether accretion-induced collapse of a white dwarf forms a low-field rapidly spinning neutron star (Michel 1987; Bailyn & Grindlay 1990) or a slowly spinning one with a high magnetic field which is subsequently spun up and undergoes field decay.

X-ray pulsars exhibit a broad correlation between their spin and pulse periods as seen in Corbet's diagram (Corbet 1984). Figure 1 shows that most LMBPs follow a similar trend. Exceptions are the two pulsars with short orbital periods but slow spin periods (PSR B0655+64 and PSR B1831−00) and, to a lesser extent, the three millisecond pulsars with orbital period near 100 days.

If millisecond pulsars are "recycled," that is, formed by accretion of matter onto a normal neutron star, the duration of the mass transfer phase depends upon the separation between the stars and therefore on the orbital period (Savonije 1983). Long-period binaries will accrete matter for a much shorter time than short-period binaries, and so a correlation between spin and orbital period is expected. On the other hand, if millisecond pulsars are formed by the accretion-induced collapse of a white dwarf, we do not expect any such correlation.

Bailes (1989) and Johnston (1992) have demonstrated that if the neutron stars in binary systems were born in Type II supernova explosions, they should possess runaway velocities related to their orbital velocity. Pulsars in short-period orbits should have large velocities, whereas those in long-period orbits should have low velocities, since those which receive large velocity kicks disrupt. If, on the other hand, LMBPs are formed by the accretion-induced collapse of a white dwarf, they should have much lower velocities, since the mass ejected during the formation of the neutron star is considerably less.

Only a few of these systems have measured velocities, but some indication of a pulsar's velocity can be inferred from its Galactic $z$-height. To attain a $z$-height of 1 kpc, an initial $z$-velocity of $\sim 50$ km s$^{-1}$ is required (Kuijken & Gilmore 1989). On average, the magnitude of the system's $z$-velocity is half that of the space velocity, so that a $z$-height of 1 kpc corresponds to a space velocity of $\sim 100$ km s$^{-1}$. The binary pulsar with the shortest period, PSR B1957+20, has a large velocity of 200 km s$^{-1}$ if the proper motion measured by Ryba & Taylor (1991) and the most recent distance estimate of Taylor & Cordes (1993) are used. The only other millisecond pulsars with short orbital periods, PSR J0034−0534, PSR J2317+1439, and PSR J1045−4509 are at $z$-heights of 850 pc, 1.4 kpc, and 700 pc, respectively, suggesting that they too have large velocities. In contrast, the pulsars PSR J2019+2425, PSR B1953+29, PSR B1800−27, and PSR B0820+02 all have small $z$-heights and large ($>70$ day) orbital periods. Although a large number of selection effects are involved in determining the sample, it appears that there is a relation between space velocity and orbital period.

Note that the two LMBPs with short orbital periods and long pulse periods (PSR B0655+64 and PSR B1831−00) are both at low $z$-heights. This suggests that they possess low velocities despite their short orbital periods. If they formed from much wider binaries but spiraled in during the giant phase of the secondary, it is possible to explain both their inferred low velocities and their slow pulse periods. We therefore postulate that the LMBPs on the main branch which extends from PSR B1957+20 to PSR B0820+02 in Figure 1 formed from normal Type II supernovae and subsequent stable mass transfer. Those in the bottom right-hand corner result from runaway mass transfer and a common-envelope spiral-in phase. The millisecond pulsars with orbital periods near 100 days do not

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[7] PSR B1257+12 is excluded, since its companions are of planetary rather than stellar mass (Wolszczan & Frail 1992).

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fit well into this scheme, however, and it is possible that they were formed by accretion-induced collapse of white dwarfs. Measurement of proper motions and parallaxes for these pulsars will help clarify these issues.

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