The Parkes Multibeam Pulsar Survey: PSR J1811−1736, a pulsar in a highly eccentric binary system

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ABSTRACT

We are undertaking a high-frequency survey of the Galactic plane for radio pulsars, using the 13-element multibeam receiver on the 64-m Parkes radio telescope. We describe briefly the survey system and some of the initial results. PSR J1811−1736, one of the first pulsars discovered with this system, has a rotation period of 104 ms. Subsequent timing observations using the 76-m radio telescope at Jodrell Bank show that it is in an 18.8-d, highly eccentric binary orbit. We have measured the rate of advance of periastron which indicates a total system mass of $2.6 \pm 0.9 \, M_\odot$, and the minimum companion mass is about $0.7 \, M_\odot$. This, the high orbital eccentricity and the recycled nature of the pulsar suggest that this system is composed of two neutron stars, only the fourth or fifth such system known in the disc of the Galaxy.

Key words: methods: observational – binaries: general – stars: neutron – pulsars: general – pulsars: individual: J1811−1736.

1 INTRODUCTION

A multibeam receiver operating at a wavelength of 20 cm has recently been installed on the 64-m Parkes radio telescope in Australia. This receiver permits simultaneous observation of 13 regions of sky, increasing the speed of surveys by the same factor. While the main motivation for the development of this system was to survey the sky for H I in the local Universe (Staveley-Smith et al. 1996), it also enables very efficient surveys for pulsars. The central observing frequency of 1374 MHz is higher than usual for all-sky pulsar surveys, but is ideal for surveys at low Galactic latitudes. At lower frequencies, sensitive surveys of the Galactic plane are limited by the high background temperature, as well as broadening of the pulses caused by dispersion and scattering of the pulsed emission by the interstellar electron plasma. All of these effects are strongly frequency-dependent and are much reduced at 1374 MHz. The Jodrell Bank and Parkes surveys of Clifton et al. (1992) and Johnston et al. (1992) were centred close to this frequency, and both were particularly successful at finding many distant and young pulsars, several of which are also X-ray and/or gamma-ray emitters and some of which are possibly associated with supernova remnants.

We are undertaking a survey for pulsars in a 10°-wide strip along the Galactic plane using the multibeam receiver on the Parkes telescope. This survey is proving remarkably successful, and the discovery of the first ∼100 pulsars is presented elsewhere (Manchester et al., in preparation). We briefly describe the experimental details of the survey in Section 2. Detailed timing observations to determine accurate pulsar positions, pulse periods, period derivatives and other parameters are an essential follow-up to any pulsar survey. Timing observations and analysis procedures for the multibeam survey pulsars are described in Section 3.

Finally, Section 4 describes a particularly interesting pulsar, PSR J1811−1736. This pulsar, one of the first discovered in the survey, is in a very eccentric orbit with a companion which is probably another neutron star. Pulsars in such binary systems in the Galactic plane are rare, there being only three known that are definite (PSRs J1518+4904, B1534+12 and B1913+16) and one that is possible (PSR B1820−11). Such systems are of great interest because both stars act essentially as point masses and they make excellent systems for studying their dynamics with high precision (e.g. Damour & Taylor 1992). In particular, the discovery of more systems like these will allow additional sensitive tests of general relativity and alternative theories of gravity, more precise measurements of neutron star masses, and better estimates of the rate of coalescence of neutron star binaries, events which are likely to be detected by future gravitational wave detectors.

2 THE PARKES MULTIBEAM SURVEY

The survey of the Galactic plane for pulsars using the multibeam receiver on the Parkes radio telescope commenced in 1997 August. The survey observations are made in a 288-MHz band centred on 1374 MHz. Receivers for each of the 13 beams are dual-channel cryogenic systems sensitive to orthogonal linear polarizations. The full width at half-power of each beam is approximately 14 arcmin and, at high Galactic latitudes, the system noise temperature of each channel is about 21 K. A large filterbank system was constructed to process the data from the 13 beams. The filterbank has 96 3-MHz channels covering the 288-MHz bandwidth for each polarization of each beam, making a total of 2496 channels. Detected signals from individual frequency channels are added in polarization pairs, high-pass filtered with a cut-off at approximately 0.2 Hz, integrated and 1-bit digitized every 250 μs, and recorded on magnetic tape (DLT) for subsequent analysis.

It is planned that the survey will cover the region ±5° about the Galactic plane from longitude 260° to 50°. The relatively long observation time of 35 min per pointing, combined with the excellent receiver noise performance and the wide bandwidth, gives a high sensitivity, with a limiting flux density for long-period pulsars of about 0.15 mJy. This is about seven times better than the previously most sensitive surveys of the Galactic plane (Clifton et al. 1992; Johnston et al. 1992). Survey observations are made on a hexagonal grid of pointings to give complete sky coverage, with adjacent beams overlapping at the half-power points. A total of 2136 pointings of the 13 beams are required to cover the survey region. At the time of writing, approximately 60 per cent of these pointings have been observed.

Analysis procedures are similar to those used in previous surveys (e.g. Manchester et al. 1996), with dedispersion followed by transformation into the modulation frequency domain using a fast Fourier transform (FFT) and harmonic summing to improve sensitivity to the typically narrow pulses. Some periodic interference is present in the data, and this is removed primarily by ignoring signals found repeatedly in undedispersed power spectra, in simultaneous data from different beams as well as from single beams at many different times. Processing is currently being carried out on networks of workstations. Initially, a single coherent FFT has been performed over each 35-min data set, giving reduced sensitivity to pulsars in short-period binary systems in which the period is varying as a result of the Doppler effects of the pulsar motion. The data are now being reprocessed in order to search for such accelerated signals.

Pulsar candidates from the initial processing are scheduled for re-observation in order to confirm their identity as pulsars. We use the centre beam of the multibeam system to make five 6-min observations, at the nominal position and four surrounding points. In most cases, this gives detections at two or three positions, confirming the pulsar and allowing an improved position to be determined with an accuracy of about 2 arcmin. Where no detection results from these observations, confirmation is attempted by means of a 35-min observation made at the nominal position. The improved positions usually permit much shorter observation times in the follow-up timing measurements, because of the higher signal-to-noise ratio obtained when the pulsar is in the centre of the telescope beam. Furthermore, they allow a smaller range of parameter space to be searched in obtaining coherent timing solutions, reducing the overall number of observations required.

At the time of writing, about 90 per cent of the observed pointings have been processed using the 'non-acceleration' search code, whilst analysis with the 'acceleration' search code has just started. Confirmation observations have been made on most of the better candidates, resulting in the detection of about 400 previously unknown pulsars, most of which are relatively distant, the median distance being ∼7 kpc. More than 150 previously known pulsars have also been detected. The current discovery rate is an unprecedented one pulsar per hour of survey observing time. This rate will decline as regions further from the Galactic plane are surveyed, but we estimate that the survey will detect at least 600 previously unknown pulsars, nearly doubling the number known before the survey commenced, and providing a significant data base for many different follow-up studies.

3 TIMING OBSERVATIONS AND ANALYSIS

After confirmation, each pulsar is subjected to a series of timing observations at either the Parkes 64-m telescope or the Lovell 76-m telescope at Jodrell Bank. Almost all of the detected pulsars north of declination −35° are being timed at Jodrell Bank. At Parkes, data are recorded using just the central beam of the multibeam system. The Jodrell Bank observations are made in a 96-MHz band centred on 1376 MHz. Dual-channel cryogenic systems receiving orthogonal circular polarizations are used, each channel having a system noise temperature of about 30 K at high Galactic latitude. Each of the two polarization signals are down-converted and fed into a multi-channel filterbank consisting of 32 3-MHz filters, before digitization.

Data from both Parkes and Jodrell Bank are dedispersed and synchronously folded at the topocentric pulsar period for ∼1 min to form subintegrations; the total integration time per observation ranges between 2 and 30 min, dependent upon the pulsar flux density. Each pulse profile obtained by summing over an observation is convolved with a high signal-to-noise ratio 'standard profile' for the corresponding pulsar, producing a topocentric time-of-arrival (TOA). These are then processed using the TEMPO program (see http://pulsar.princeton.edu/tempo), which converts them to barycentric TOAs at infinite frequency and performs a multiparameter fit for the pulsar parameters. Barycentric corrections are obtained using the Jet Propulsion Laboratory DE200 Solar system ephemeris (Standish 1982). Except for especially interesting cases, we make timing observations of each pulsar over about 12 months, resulting in an accurate position, period, period derivative and dispersion measure (DM). This provides the basic parameters necessary for follow-up studies such as investigations of the Galactic distribution of pulsars, studies of the interstellar medium and high-energy observations.

These observations also reveal pulsars that are members of binary systems. After detection, such pulsars are observed more intensively to determine their binary parameters. Of the new pulsars detected so far, seven have already been identified as members of binary systems, and one of these is described in the next section.

4 PSR J1811–1736

PSR J1811−1736 was initially observed on 1997 August 3 and revealed as a candidate with a 104-ms period and DM of 477 cm^{-3} pc. It was confirmed as a pulsar on 1997 December 19. This observation gave a period that was substantially different
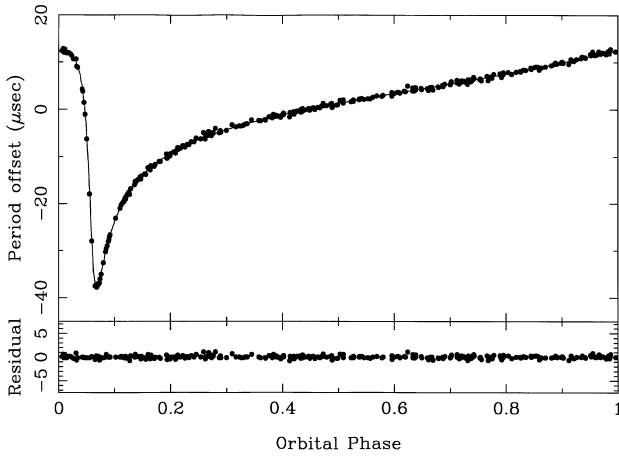
Figure 1. The observed variation of the barycentric period of PSR J1811−1736 over the 18.8-d orbital period measured using the 76-m Lovell telescope at Jodrell Bank (top). The residuals from the model given in Table 1 and shown as the continuous line in the top diagram are shown in the bottom plot. The orbital phase is measured from the time of the ascending node.

Table 1. Parameters of PSR J1811−1736.

Measured parameters	
Right ascension (J2000)	$18^h11^m55^s.01(1)$
Declination (J2000)	$-17°36'36''.9(13)$
Dispersion measure (cm^{-3} pc)	477(10)
Period (s)	0.104 181 954 734(3)
Epoch of period (MJD)	51050.0
Period derivative	$1.8(6) \times 10^{-18}$
Orbital period (days)	18.779 168(4)
Projected semi-major axis (lt-s)	34.7830(8)
Eccentricity	0.828 02(2)
Epoch of periastron (MJD)	51044.037 02(3)
Angle of periastron (degrees)	127.661(2)
Rate of advance of periastron (° yr^{-1})	0.009(2)
Rate of change of projected semimajor axis	$< 3 \times 10^{-11}$
rms timing residual (ms)	1.0
Flux density at 1400 MHz (mJy)	0.7(2)
Interstellar scattering at 1376 MHz (ms)	21(3)
Derived parameters	
Galactic longitude (degrees)	13.4
Galactic latitude (degrees)	0.7
Distance (kpc)	6(1)
Characteristic age (yr)	$9^{+4}_{-2} \times 10^8$
Surface magnetic field (G)	$1.4(2) \times 10^{10}$
Total system mass ($M_\odot$)	2.6(9)
Mass function ($M_\odot$)	0.128

from the initial discovery period, indicating a possible binary nature. This was confirmed by a series of observations at Jodrell Bank during the beginning of 1998 which demonstrated that the pulsar was a member of a binary system in a highly eccentric orbit. Fig. 1 shows the measured period variation of PSR J1811−1736 through the orbital period of 18.8 d. Subsequently, we performed a phase-coherent analysis of the arrival times over a 16-month period. The results are summarized in Table 1. Errors given in parentheses refer to the last quoted digit and are twice the formal standard error.

Using the Taylor & Cordes (1993) model for the electron density distribution in the Galaxy and the measured DM, we obtain an estimated distance for PSR J1811−1736 of $d \sim 6$ kpc.
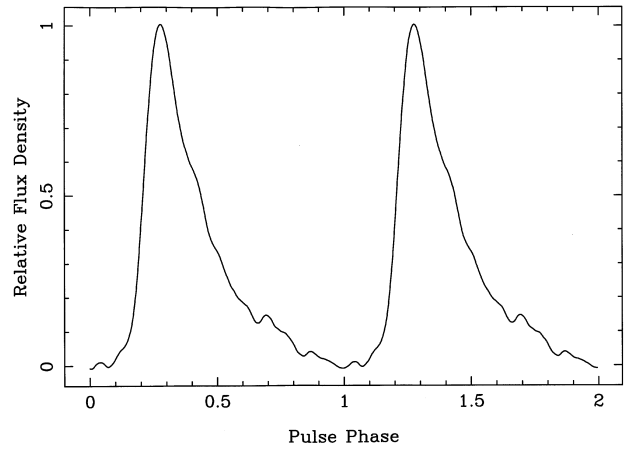

Figure 2. The pulse profile of PSR J1811−1736 observed at a central frequency of 1376 MHz, covering two complete periods of pulse phase. The time resolution is approximately 4 ms or 0.04 in pulse phase. The features on the trailing edge are at about the level expected from random noise and are unlikely to be significant.

With the measured flux density at 1400 MHz of $S_{1400} = 0.7$ mJy (Table 1), the luminosity of this pulsar at 1400 MHz is $L_{1400} \equiv S_{1400}d^2 = 25$ mJy kpc^2. The pulsar has not yet been detected at other frequencies, mainly because of the large amount of scattering at lower frequencies. However, we can get a rough estimate of its luminosity at $\sim$400 MHz by assuming a typical pulsar spectral index of ~ -1.6. We obtain $L_{400} \approx 200$ mJy kpc^2, indicating that this is a relatively luminous pulsar, significantly above any low-luminosity cut-off in the luminosity distribution of Galactic disc pulsars at 400 MHz of 1 mJy kpc^2 or lower (Lorimer et al. 1993; Lyne et al. 1998).

The average pulse profile of PSR J1811−1736 is shown in Fig. 2. It is very asymmetric, with a rapidly rising leading edge with an approximately exponential tail following the peak. The tail is detectable throughout the period and is characteristic of the effects of multipath propagation in the interstellar medium, more usually observed at lower frequencies. In such scattering, the time-scale of the exponential, τ_s, varies with frequency, ν, approximately as $\tau_s \propto \nu^{-4}$. Over the 288-MHz band of the Parkes receiver, τ_s is found to vary by about a factor of 2, consistent with such a variation. The amount of scattering is unusually large for a pulsar with this DM observed at around 1400 MHz: the Taylor & Cordes (1993) model predicts $\tau_s \approx 2$ ms, while the observed τ_s is about 20 ms. This accounts for the rather large rms timing residual reported in Table 1.

As listed in Table 1, the spin parameters for PSR J1811−1736 imply a large 'characteristic age' of $\tau = P/2\dot{P} = 9 \times 10^8$ yr, and a relatively low implied surface dipole magnetic field strength of $B = 3.2 \times 10^{19}\sqrt{P\dot{P}} = 1.4 \times 10^{10}$ G. Such spin parameters are typical of the known double-neutron-star systems (Taylor et al. 1995; Nice, Sayer & Taylor 1996). This pulsar is located below the 'spin-up line' on a period–magnetic field diagram (see e.g. Phinney & Kulkarni 1994, fig. 1; Lyne & Graham-Smith 1998, p. 115), suggesting that it was spun up at an earlier stage in its history.

In addition to the standard astrometric, spin and Keplerian orbital parameters, a satisfactory fit to the timing data requires inclusion of the rate of orbital precession of the pulsar in the fitted parameters, giving $\dot{\omega} = 0°.009 \pm 0°.002$ yr^{-1}. Assuming that the companion star is a compact object, that tidal effects are negligible
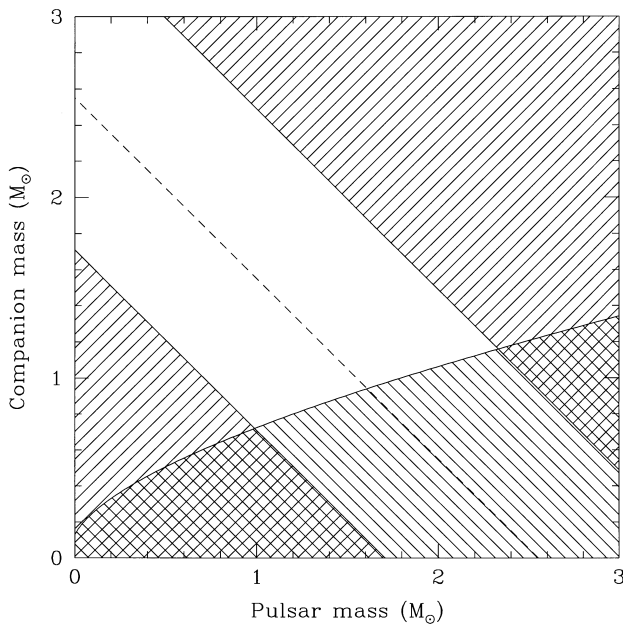
Figure 3. Constraints on the masses of PSR J1811−1736 and its companion, obtained from the observed mass function and the measured rate of advance of periastron. The allowed component masses lie in the clear area of the diagram (see text).

and that the measured rate of advance of periastron is due to general relativistic effects alone, we have (e.g. Will 1993)

$$\dot{\omega} = 3(2\pi/P_b)^{5/3}(1 - e^2)^{-1}\, T_\odot^{2/3}(m_1 + m_2)^{2/3}, \tag{1}$$

where $T_\odot = G M_\odot/c^3 = 4.925 \times 10^{-6}$ s, P_b is the binary period, e is the binary eccentricity, and m_1 and m_2 are the pulsar and companion masses, in solar masses. The measurement of $\dot{\omega}$ yields a total system mass of $m_1 + m_2 = 2.6 \pm 0.9\,M_\odot$, or an average component mass of $1.3 \pm 0.4\,M_\odot$. This compares with the average mass of neutron stars measured in other binary pulsar systems of $1.35 \pm 0.04\,M_\odot$ (Thorsett & Chakrabarty 1999). The constraints on the masses of the two stars can be most readily seen in Fig. 3. The region under the convex curve is excluded because of the requirement that $\sin i \leq 1$ in the 'mass function',

$$f_1(m_1, m_2, i) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = \frac{4\pi^2}{T_\odot}\frac{(a_1 \sin i)^3}{P_b^2}, \tag{2}$$

where $a_1 \sin i$ is the projected semimajor axis of the pulsar orbit. From Fig. 3 we see that $m_1 < 2.3\,M_\odot$ and that $m_2 > 0.7\,M_\odot$. These constraints on the individual and average masses of the system, the lack of eclipses, the low magnetic field of the pulsar and the high binary eccentricity all suggest that the pulsar companion is another neutron star. If so, this is only the fourth or fifth double-neutron-star system discovered in the Galactic disc (e.g. Nice et al. 1996).

If the companion were a main-sequence or giant star, in addition to relativistic effects, classical effects could also contribute to the measured value of $\dot{\omega}$ (e.g. Lai, Bildsten & Kaspi 1995; Kaspi et al. 1996; Wex 1998). For a pulsar of mass $m_1 = 1.35\,M_\odot$, the relativistic contribution always dominates. However, for a small range of companion masses around $1\,M_\odot$, some remaining $\dot{\omega}$ could in principle be attributed to a classical quadrupole moment Q in the companion star. The neutron star should raise a tide in a companion having radius R_2 such that

$Q \sim km_1 R_2^2(R_2/r)^3$, where k is the apsidal constant and r is the instantaneous centre-of-mass separation (Lai et al. 1995). However, given the orbital parameters and estimates for k from stellar modelling (Hejlesen 1987; Claret & Gimenez 1991), the values of Q permitted by the observations are much smaller than would be expected. Thus a main-sequence or giant companion should result in a much larger $\dot{\omega}$ than is observed. This conclusion is not very sensitive to the choice of m_1.

We note that a rapidly rotating main-sequence star companion, with spin axis sufficiently misaligned with the orbital angular momentum, could result in a spin-induced quadrupole that precesses the orbit in the retrograde direction, cancelling the tidal effect. However, this is most unlikely as it requires fine-tuning the spin and tidal effects to be surprisingly close in magnitude.

Recently, the companion in another double-neutron-star candidate system (PSR B2303+46) has been shown to be a white dwarf (van Kerkwijk & Kulkarni 1999). It is therefore important to assess what other constraints exist on the nature of the companion. Searches of a number of optical telescope archives revealed that the only available images were from the Digital Sky Survey V band, obtained at the UK Schmidt telescope. No sources are visible in the vicinity of the pulsar down to the plate limit of $M_V \sim 16$. Unfortunately, this can only conclusively rule out a red giant companion, and a deeper image would be required to test whether the companion is a main-sequence star ($M_V \sim 19$) or a white dwarf ($M_V \sim 27$).

We note that there is no evidence of occultation of the pulsar at any phase of the orbit (Fig. 1). The closest approach of the two stars depends upon the unknown inclination angle i, but is several solar radii, making the occultation of the pulsar by a solar-mass main-sequence companion star possible, but rather unlikely. These observations do not therefore distinguish between a main-sequence and a compact companion. However, the whole orbit is smaller than a giant star, ruling out the possibility of such a companion.

The absence of significant tidal or quadrupole effects on $\dot{\omega}$ suggests that the companion star is compact and therefore either another neutron star or a white dwarf. Such binary systems are generally thought to evolve from two initially massive stars. The formation of a neutron star in the supernova collapse of the primary is expected in due course to be followed by a common-envelope and spiral-in stage. During this time, it is detectable as an accreting high-mass X-ray binary system (e.g. Verbunt 1993), prior to the formation of a second neutron star or a white dwarf. If the pulsar is the second-formed compact object, it is not clear how the magnetic field became so small, an attribute which is generally thought to arise during mass transfer. If the pulsar were the original neutron star, the ensuing mass transfer would have reduced the magnetic field. However, this would also have circularized the orbit, which would have remained that way if the companion evolved to a white dwarf. Since the orbit is eccentric, we must conclude that it was probably the formation of a second neutron star that gave rise to the eccentricity.

In the future, this binary system is not likely to evolve significantly. Because of its relatively large orbital size, it does not emit significant amounts of gravitational radiation: using the formulae of Peters (1964), we calculate that the coalescence time of the PSR J1811−1736 system is about 10^{12} yr. Therefore systems such as this make a negligible contribution to the neutron star merger rate calculations which are important for gravity wave detectors such as LIGO.

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