The High Time Resolution Universe Pulsar Survey – II. Discovery of five millisecond pulsars

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ABSTRACT

We present the discovery of five millisecond pulsars found in the mid-Galactic latitude portion of the High Time Resolution Universe (HTRU) survey. The pulsars have rotational periods from ~2.3 ms to ~7.5 ms, and all are in binary systems with orbital periods ranging from ~0.3 to ~150 d. In four of these systems, the most likely companion is a white dwarf, with minimum masses of ~0.2 M⊙. The other pulsar, J1731–1847, has a very low mass companion and exhibits eclipses and is thus a member of the ‘black widow’ class of pulsar binaries. These eclipses have been observed in bands centred near frequencies of 700, 1400 and 3000 MHz, from which measurements have been made of the electron density in the eclipse region. These measurements have been used to examine some possible eclipse mechanisms. The eclipse and other properties of this source are used to perform a comparison with the other known eclipsing and ‘black widow’ pulsars.

These new discoveries occupy a short-period and high-dispersion measure (DM) region of parameter space, which we demonstrate is a direct consequence of the high time and frequency resolution of the HTRU survey. The large implied distances to our new discoveries make observation of their companions unlikely with both current optical telescopes and the Fermi Gamma-ray Space Telescope. The extremely circular orbits make any advance of periastron measurements highly unlikely. No relativistic Shapiro delays are obvious in any of the systems although the low flux densities would make their detection difficult unless the orbits were fortuitously edge-on.

Key words: pulsars: general – pulsars: individual: PSR J1125–5825 – pulsars: individual: PSR J1708–3506 – pulsars: individual: PSR J1731–1847 – pulsars: individual: PSR J1801–3210 – pulsars: individual: PSR J1811–2405.

1 INTRODUCTION

Millisecond pulsars (MSPs) are neutron stars (NSs) with rapid rotation rates that are believed to be formed in binary systems when the NS accretes matter from the companion, causing a ‘spin-up’ in the NS’s rotation rate (e.g. Alpar et al. 1982). This process results in pulsars with spin periods between 1 and 100 ms and magnetic field strengths less than 10¹⁰ G. Those systems with spin periods less than about 20 ms are thought to have low-mass companions, while those with periods between 20 and 100 ms are thought to have been spun up by a heavy white dwarf (WD) or NS companion. During the spin-up phase, the heating caused by accretion leads to the emission of X-ray radiation (Davidson & Ostriker 1973). These accreting systems are known as high-mass and low-mass X-ray binaries (HMXBs and LMXBs, respectively) depending upon the companion mass (see Bhattacharya & van den Heuvel 1991 for details of evolution). The link between LMXBs and MSPs was not confirmed until pulsations with a period of 2.4 ms were observed in the accreting X-ray binary, SAX J1808.4–3658 (Wijnands & van der Klis 1998). This link has more recently been reinforced by the discovery of PSR J1023+0038 (Archibald et al. 2009), where radio

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emission is likely to have only switched on recently after an LMXB phase.

In contrast to this evolutionary model, however, around 20 per cent of the MSP population appear to be isolated bodies, including the first MSP to be discovered, PSR B1937+21 (Backer et al. 1982). Therefore, if this scenario is correct, and the isolated MSPs are the descendants of the eclipsing MSPs, we might expect some of them to eventually ablate their companions until nothing remains (Ruderman, Shaham & Tavani 1989). The discovery of the so-called ‘black widow’ pulsar, PSR B1957+20 (Fruchter, Stinebring & Taylor 1988), and other similar systems (e.g. PSR J2051−0827, Stappers et al. 1996), provides some evidence of this process taking place.

In these systems, the pulsar’s companion is typically of very low mass (∼0.02 M⊙), and the pulsar is eclipsed by the companion for at least 10 per cent of the orbit. As the pulsar approaches eclipse, the pulses experience a delay due to the additional ionized gas through which the radiation has to pass, while outflowing material from the companion often gives rise to anomalous eclipses away from superior conjunction. However, the time-scale over which the ablation process would lead to the companion being destroyed is far too long to explain the abundance of isolated MSPs (Stappers et al. 1996). Clearly, other mechanisms such as tidal disruption are needed to explain the existence of this group.

The discovery of PSR J1903+0327 (Champion et al. 2008) further challenges the conventional formation scenarios. Not only is the pulsar’s companion a main-sequence star, but the orbit is also highly eccentric (e = 0.44), neither of which are predicted by the standard formation scenarios. Three alternative theories for the formation have been proposed: (i) the pulsar was born in an eccentric orbit, spinning rapidly; (ii) the pulsar was spun up in a globular cluster before being ejected into the Galactic disc and (iii) the recycling of the pulsar in a triple system (Champion et al. 2008). Freire et al. (2010) have since confirmed that the main-sequence star is the companion and excluded the possibility that PSR J1903+0327 is currently a member of a triple system, but maintain that the pulsar was born in a triple system, from which the component originally responsible for the spin-up of PSR J1903+0327 has been ejected. However, if any of the alternatives are viable, we need to understand how many MSPs form via this channel, and to do that a larger sample of MSPs is required.

Beyond improving our understanding of binary star evolution, there are many areas of pulsar science which benefit from the discovery of recycled pulsars. The discovery of binaries with, for example, a NS or black hole companion offer the chance to test General Relativity (GR) and other theories of gravity in the strong field regime (e.g. Kramer et al. 2004, 2006). The case of a pulsar with a WD companion also offers the possibility of observing effects predicted by GR. For example, PSR J1909−3744 is in a 1.5-d orbit with a companion of mass 0.2 M⊙, where Shapiro delay has been observed, allowing the measurement of both the companion and pulsar masses (Jacoby et al. 2003, 2005).

The NS equation of state is currently poorly understood, and the predictions of NS masses and radii vary dramatically for different models (Lattimer & Prakash 2004). One way to place a limit on these parameters is to identify the limiting rotation frequency, beyond which the NS would break apart. Currently, the most rapidly rotating known pulsar is PSR J1748−2446ad (Hessels et al. 2006), which rotates at 716 Hz; the discovery of an MSP rotating even faster than this could rule out some NS equation of state models (Lattimer & Prakash 2007, 2010). By constraining the maximum mass of a NS, it should also be possible to eliminate many models of the equation of state (Lattimer & Prakash 2004). To do this, one can use binary effects such as Shapiro delay which allow the pulsar mass to be measured (e.g. Lyne et al. 2004), an effect which is most measurable for those systems where the pulsar is found to have a massive companion or a near edge-on orbit (e.g. Demorest et al. 2010). Therefore, the discovery of more systems where the NS mass can be measured (e.g. Freire et al. 2010) would contribute to the understanding of the NS equation of state. For some pulsars in binary systems, it has been possible to observe the companion optically (e.g. Bassa et al. 2006) and measure its radial velocity as a function of orbital phase. However, for WD companions, often the faintness of the companion only allows the measurement of a temperature, from which a mass must be estimated using evolutionary models (van Kerkwijk 1996).

Currently, pulsar timing arrays (Hobbs et al. 2009; Jenet et al. 2009; Ferdman et al. 2010) are attempting to detect gravitational waves by the correlation of arrival times (e.g. Jenet et al. 2006) from pulsars. These arrays require long-term, high-precision timing observations with high signal-to-noise ratio (S/N); MSPs, with their short spin periods and stable rotation rates, are well suited for these timing arrays (Verbiest et al. 2009). However, not all MSPs have the narrow pulse profiles, regular rotation and high flux density required to obtain high timing precision, nor is the distribution of the known sources as uniform over the sky as desired (see e.g. Hellings & Downs 1983). Hence, further discoveries from pulsar surveys may make important contributions to pulsar timing arrays and improve their sensitivity to the stochastic background of gravitational waves.

The largest previous pulsar survey, which found many of the known MSPs, was the Parkes multibeam pulsar survey (PMTS) by Manchester et al. (2001), which surveyed the area of the Galactic plane bounded by 260° ≤ l ≤ 50°, |b| ≤ 5°, discovering 24 MSPs. At higher Galactic latitudes, the Swinburne intermediate-latitude pulsar survey (260° ≤ l ≤ 50°, 5° ≤ |b| ≤ 15°), using a similar observing system except for a reduced sampling time, discovered a further eight MSPs (Edwards & Bailes 2001; Edwards et al. 2001). However, these surveys were limited by the relatively low sensitivity to MSPs, and by sampling with 2 bits (compared to 1 bit per sample in the PMTS) sensitivity is further increased by reducing losses due to digitization. The High Time Resolution Universe (HTRU) survey (Keith et al. 2010) aims to make use of these improvements in backend technology to perform a survey of the entire southern sky with much-improved sensitivity to rapidly rotating pulsars.

The ionized interstellar medium disperses the pulses emitted by radio pulsars as they traverse it. When removing this dispersion, increased frequency resolution allows this correction to be made with reduced smearing of the pulses. The increased time resolution provides greater sensitivity to short-period pulses, such as those from MSPs, and by sampling with 2 bits (compared to 1 bit per sample in the PMTS) sensitivity is further increased by reducing losses due to digitization. The High Time Resolution Universe (HTRU) survey (Keith et al. 2010) aims to make use of these improvements in backend technology to perform a survey of the entire southern sky with much-improved sensitivity to MSPs.

The ongoing PALFA survey at Arecibo (Cordes et al. 2006) and the GBT 350-MHz survey (Boyles et al. 2010) have each discovered several MSPs which occupy the short-period and high-dispersion measure (DM) region of parameter space which we look to probe with HTRU. In particular, the discovery, as previously mentioned, of PSR J1903+0327 (Champion et al. 2008) as part of the PALFA survey stands out with a rotation period of 2.15 ms and a DM of 297.5 cm−3 pc as evidence that time resolution of 64 µs allows this parameter space to be probed.

In this paper, we outline the spin and orbital parameters of five MSPs discovered as part of the HTRU survey, compare the...
properties of these pulsars to the previously known population and
study in detail the eclipses that one of them displays. These
discoveries have been made with ~30 per cent of the survey region
observed, indicating that we might expect tens of MSPs to be dis-
covered when the survey is completed.

2 OBSERVATIONS

2.1 Discovery and timing

The HTRU survey (Keith et al. 2010) is broken into three distinct
components with different scientific objectives: the low latitude
region covering Galactic latitude |b| < 3°.5; the mid-latitude region
covering |b| < 15° and the high latitude region which covers the
remaining sky below declination +10°. The mid-latitude survey is
designed to find MSPs that were missed by previous surveys due to
excessive dispersion smearing but are still bright enough to be found
in ~10 min. Observations are made using the 13-beam multibeam
receiver on the 64-m Parkes radio telescope, which has a half-power
beamwidth of ~0.23. Data were then processed using the HITRUN
pipeline described in Keith et al.; all five MSPs were discovered in
the mid-latitude component of this survey, which covers an area of
the Galactic plane bounded by −120° < l < 30°, |b| ≤ 15° with
observations 540 s in duration. Full details of the survey parameters
are given in Table 1.

After their discovery and confirmation, timing observations of
these MSPs were made with baselines ranging from 250 d to more
than 400 d. Those which are visible from Jodrell Bank Observatory –
PSR J1731−1847, PSR J1801−3210 and PSR J1811−2405 – were
regularly observed with the 76-m Lovell Telescope in a band centred
at 1524 MHz, while PSR J1125−5825 and PSR J1731−3506 were
observed with the 64-m Parkes radio telescope in a band centred at
1369 MHz (these Jodrell Bank and Parkes data are, hereafter, ‘the
20-cm band’). At Jodrell Bank, observations were made approxi-
mately once per week, and Parkes observations were more sporadic,
with gaps between observations sometimes lasting as long as three
months. Timing observations at both observatories were made using
digital filter banks (DFBs). Flux-calibrated observations using the
Parkes DFB were used for measurement of the source fluxes. Cali-
bration was performed using routines included in PSRCHIVE (Hotan,
van Straten & Manchester 2004) and with observations of both a
calibrator source (Hydra A) and a pulsed calibrator.

In order to study the pulse profile evolution with frequency, ob-
servations were made of some of the sources using the 10/50 cm
band receiver mounted on the Parkes telescope (the bands have
centre frequencies of 732 and 3094 MHz), and using the Wester-
bork Synthesis Radio Telescope (WSRT) and the PuMA II backend

### Table 1. Observational parameters for the mid-latitude portion of the HTRU survey.

| Parameter                   | Value |
|-----------------------------|-------|
| Number of beams             | 13    |
| Polarizations/beam          | 2     |
| Centre frequency            | 1352 MHz |
| Frequency channels          | 1024 × 390.625 kHz |
| Galactic longitude range    | −120° to 30° |
| Galactic latitude range     | |b| ≤ 15° |
| Sampling interval           | 64 µs |
| Bits/sample                 | 2     |
| Observation time/pointing   | 540 s |

*154 of these channels are then masked to remove interference.

(Karuppusamy, Stappers & van Straten 2008) in a band centred at
347 MHz (hereafter, ‘the 92-cm band’). Observations were made
with the WSRT for each of the pulsars with δ > −35°; however,
neither PSR J1801−3210 nor PSR J1731−1847 have been detected
at this wavelength. The system parameters for all the observations
are shown in Table 2.

The timing solutions for each of the systems are shown in
Table 3. The first quantities given in this table are the positions
of the sources after timing over the specified range of dates. This
timing has allowed the positions to be fitted to subarcsecond preci-
sion, with positional errors as given. Four of these new discoveries
lie within 5° of the Galactic plane, with only PSR J1731−1847
outside this range, with b = 8.15.

2.2 Orbital and spin parameters

The pulse periods of the newly discovered pulsars range from 2.3 ms
(PSR J1731−1847) to 7.5 ms (PSR J1801−3210) (see Table 3).
The change in period seen in confirmation observations of all five
sources made it apparent that the pulsars are in binary systems.
With subsequent observations, we were able to fit for the observed
variation in pulse period with time and deduce a set of orbital pa-
rameters for each pulsar. In order to precisely measure the spin
and orbital parameters of each pulsar, the regular timing observations
in the 20-cm band were used to produce a set of time-of-arrival (TOA)
measurements. Using the standard pulsar timing procedure (e.g.
Lorimer & Kramer 2005), these TOAs were used to fit for each
of the parameters presented in Table 3 using the Tempo2 pulsar timing
package (Hobbs, Edwards & Manchester 2006). The locations of
these pulsars in the P−P plane are shown in Fig. 1 and are seen to
lie towards the lower end of the period distribution, with each of the
new discoveries fitting in the region traced by the previously known
population with short spin periods.

The transverse velocity, \( V_T \), of a pulsar at distance \( d \) makes a
contribution to the measured value of \( P \) in what is known as the
Shklovskii effect (Shklovskii 1970)

\[
\frac{\dot{P}}{P} = \frac{1}{c} \frac{V_T^2}{d}.
\]

We can then calculate the value of \( V_T \), given some contribution to
\( \dot{P}/P \). Assuming this contribution is 10 per cent for each MSP, we
find that PSR J1708−3506 and PSR J1731−1847 would be required
to have very large values of \( V_T \), 670 and 350 km s\(^{-1}\), respectively.
The other three MSPs would require \( V_T < 100 \) km s\(^{-1}\), which are
‘realistic’ values (Toscano et al. 1999); and if the Shklovskii con-
tribution was as high as 50 per cent for these three, \( V_T \) would only
need to be ~100 km s\(^{-1}\). It seems feasible, therefore, that there is a
Table 3. Observed and derived parameters for the new MSPs. The DM distance has been estimated using the model of Cordes & Lazio (2002), while a pulsar mass of 1.4 M\(_\odot\) has been assumed in calculating companion masses.

| Parameter                  | J1125−5825 | J1708−3506 | J1731−1847 | J1801−3210 | J1811−2405 |
|----------------------------|------------|------------|------------|------------|------------|
| Right ascension (J2000)    | 11:25:44.3654(3) | 17:08:17.623(1) | 17:31:17.6072(2) | 18:01:25.8890(2) | 18:11:19.8539(2) |
| Declination (J2000)        | −58:25:16.867(5) | −35:06:22.857(7) | −18:47:32.741(4) | −32:10:53.721(1) | −24:05:18.727(2) |
| Galactic longitude (°)     | 291.89     | 350.47     | 6.89       | 358.92     | 7.07       |
| Galactic latitude (°)      | 2.60       | 3.12       | 8.15       | −4.58      | −2.56      |
| Discovery S/N              | 11         | 18         | 14         | 11         | 13         |
| Offset from survey beam centre (°) | 0.12   | 0.05       | 0.06       | 0.03       | 0.17       |
| TOA range (MJD)            | 55135−55431 | 55127−55461 | 55148−55399 | 54996−55409 | 55131−55389 |
| P (ms)                     | 3.1021391895048(4) | 4.50515894826(6) | 2.344555833757(6) | 7.45358373412(2) | 2.660593316901(1) |
| P (× 10^{-20})             | 5.9635(5)  | 2.34(4)    | 2.49(1)    | 0.2659(7)  | 1.36(2)    |
| DM (cm^{-3} pc)            | 124.81(5)  | 146.82(2)  | 106.56(6)  | 176.7(4)   | 60.64(6)   |
| DM distance (kpc)          | 2.6        | 2.8        | 2.5        | 4.0        | 1.8        |
| \(S_{\text{1.4GHz}}\) (mJy) | 0.44(2)    | 0.53(1)    | 0.60(2)    | 0.21(1)    | 0.37(1)    |
| \(L_{\text{1.4GHz}}\) (mJy kpc^{-2}) | 3.0       | 2.6        | 3.8        | 3.4        | 3.2        |
| \(\tau_c\) (yr)            | 8.2 \times 10^8 | 3.1 \times 10^9 | 1.5 \times 10^9 | 4.5 \times 10^9 | 3.1 \times 10^9 |
| \(B_{\text{surf}}\) (G)    | 4.3 \times 10^8 | 3.2 \times 10^8 | 2.3 \times 10^8 | 1.4 \times 10^9 | 1.9 \times 10^9 |
| \(B_c\) (G)                | 1.3 \times 10^8 | 3.2 \times 10^8 | 1.7 \times 10^8 | 3.1 \times 10^9 | 9.3 \times 10^9 |
| \(E\) (erg s^{-1})        | 7.9 \times 10^{34} | 9.9 \times 10^{33} | 7.6 \times 10^{34} | 2.5 \times 10^{32} | 2.8 \times 10^{34} |
| \(E_{\text{c}}\) (erg kpc^{-2} s^{-1}) | 1.2 \times 10^{34} | 1.2 \times 10^{33} | 1.2 \times 10^{34} | 1.6 \times 10^{31} | 8.6 \times 10^{33} |
| Binary model               | ELL1       | ELL1       | ELL1       | ELL1       | ELL1       |
| Orbital period (d)         | 76.4032169(4) | 149.13318(1) | 0.311341424(4) | 20.7716995(3) | 6.27230204(2) |
| \(a\sin i\) (light-second) | 33.638536(1) | 33.58233(5) | 0.1201594(9) | 7.809320(5) | 5.705662(5) |
| TASC (MJD)                 | 55112.348809(1) | 55132.23096(2) | 55132.313000(8) | 55001.934481(3) | 55136.186237(1) |
| \(\epsilon_1\)            | −0.000025349(5) | 0.00000042(6) | 0.00000001(1) | 0.00000001(1) | 0.00000001(1) |
| \(\epsilon_2\)            | −0.00004445(6) | −0.00002452(5) | 0.00000001(1) | 0.00000001(1) | 0.00000001(1) |
| \(e\)                      | 0.000025720(5) | 0.00002445(2) | 0.00014(1)     | 0.000004(1)    | 0.0000024(4)   |
| \(\omega\) (°)             | 260.140(2)  | 179.91(5)  | 264(5)       | 290(20)      | 253(7)      |
| Min. \(m_c\) (M_{\odot})  | 0.26       | 0.16       | 0.037       | 0.15        | 0.24       |
| Med. \(m_c\) (M_{\odot})  | 0.30       | 0.19       | 0.043       | 0.17        | 0.28       |
| rms of fit (µs)            | 5.538      | 7.771      | 6.339       | 29.050      | 5.539      |
| \(\chi^2\) of fit         | 0.95       | 1.3        | 7.8         | 1.3         | 1.3        |

Figure 1. \(P−\dot{P}\) diagram of the MSPs, divided by binary ‘type’. Lines of constant \(E\) cross the population at (from left to right) \(10^3\), \(10^4\), and \(10^5\) erg s^{-1}. Pulsars in globular clusters have been excluded from this figure.

In this work, we have used the ELL1 pulsar timing model (as outlined in the appendix of Lange et al. 2001) to fit for all the relevant spin and binary parameters in each of the pulsars. This model is suitable for modelling the orbits of low-eccentricity systems, and for PSR J1125−5825 and PSR J1708−3506, it gives a statistically significant value for the orbital eccentricity. With the exception of PSR J1731−1847, the reduced \(\chi^2\) is 

\[\chi^2\] for these pulsars, which in turn implies that the values of \(E\) \(\propto\) \(\dot{P}\) and \(B_{\text{surf}}\) \(\propto\) \(P^{1/2}\) are overestimated and \(\tau_c\) \(\propto\) \(P^{-1}\) underestimated in Table 3.

\[
f(m_p, m_c) = \frac{(m_c \sin i)^3}{(m_p + m_c)^3} = \frac{4\pi^2}{G} \frac{x^3}{P_0^8},
\]

where \(G\) is Newton’s gravitational constant and \(P_0\) is the orbital period of the pulsar in the binary system, and \(i\) is the inclination of the orbit. Assuming a pulsar mass of 1.4 M\(_\odot\), the mass function may be solved for the mass of the companion as a function of orbital
inclination. Solving for $i = 90^\circ$ gives the minimum mass of the companion, and $i = 60^\circ$ gives the median mass; each of these values are given in Table 3. Apart from PSR J1731$-1847$, the companions to these pulsars have median mass values of $\sim 0.2 M_\odot$, indicating that they are typical pulsar–WD binary systems. PSR J1731$-1847$, however, has a companion with a very low median mass, only 0.043 $M_\odot$. As this low mass suggests (e.g. Ryba & Taylor 1991; Stappers et al. 1996), PSR J1731$-1847$ displays eclipses, which are discussed in detail in Section 4.

2.3 Pulse profiles

The pulse profiles of each pulsar in the different observing bands are shown in Fig. 2. PSR J1125$-5825$ and PSR J1811$-2405$ each display an interpulse, trailing the main pulse by $\sim 0.55$ and $\sim 0.45$ in pulse phase, respectively. The spectral properties of the two interpulses are different at shorter wavelengths – the interpulse of PSR J1125$-5825$ is not visible in the 10-cm band, probably due to the low S/N of the profile. However, in PSR J1811$-2405$ the flux of the interpulse increases relatively to the main pulse at 10 cm, indicating that the interpulse has a flatter spectrum than the main pulse. This has been observed previously, both for normal pulsars (e.g. Biggs et al. 1988) and MSPs J2322$+2057$ (Nice, Taylor & Fruchter 1993), J1012$+5307$ (Kramer et al. 1999) and B1855$+09$ (Kijak et al. 1997). The interpulse of PSR J1125$-5825$ also appears to be complex, consisting of at least two components in the 20-cm band, while the profile of PSR J1811$-2405$ displays off-pulse emission trailing the interpulse that can be seen in the pulse profiles at 10 and 20 cm.

The main peaks of the pulse profiles of PSR J1731$-1847$ and PSR J1811$-2405$ are narrow in comparison to the other new discoveries. This property can make high-precision timing of an MSP an easier task; however, the eclipses of PSR J1731$-1847$ make it unlikely to be suitable for pulsar timing arrays. The profiles of PSR J1708–3506, at 20 cm, PSR J1801–3210, at 50 cm, and PSR J1811–2405, at 92 cm, display broadening of the pulse with respect to the profiles at shorter wavelengths. In these cases, this broadening can be attributed to the scattering of pulses by the interstellar medium, as the high frequency resolution of the observing systems precludes the possibility that this is caused by residual DM smearing across a frequency channel, while the observation in the 92-cm band has been coherently dedispersed.

Using the empirical fit of Bhat et al. (2004), we would expect the scattering tail in these observations to have a 1/e time-scale of 0.7 ms for PSR J1801–3210 and 0.1 ms for PSR J1811–2405, but only 0.02 ms for PSR J1708–3506. Since there is a large amount of scatter around the Bhat et al. relationship, the fact that this time-scale is slightly underestimated in the first two cases, each case is not likely to be significant – for comparison, the NE2001 electron distribution model (Cordes & Lazio 2002) predicts scatter broadening times of 0.01, 0.4 and 0.5 ms for PSR J1708–3506, PSR J1801–3210 and PSR J1811–2405, respectively. It is also possible that this pulse broadening is due to intrinsic evolution of the pulse profile with observing frequency, and for PSR J1708–3506, it is unclear whether this broadening is due to a second component which trails the main peak. This component may be present, though faint, in the 10-cm observation.

For the two pulsars which were observed, but not detected, at 92 cm, assuming the standard relationship for pulse scattering as
a function of wavelength (e.g. Lambet & Rickett 2000), \( \tau_s \propto \lambda^{(1/3)} \), the 1/e time-scale for scattering, \( \tau_s \), should be increased by a factor of \( \sim 11 \) at 92 cm compared to 50 cm. In the case of PSR J11801–3210, it seems likely that the increased scattering could be responsible for smearing the pulse over more than a pulse period. For PSR J1731–1847, however, the observations were neither made well away from orbital phase 0.25 (removing the possibility of eclipse), nor does it appear that the scattering would be severe enough to smear the pulse by more than a pulse period, making it likely that the flux density at this wavelength was below the detection threshold, implying a relatively flat spectral index, or a spectral break.

2.4 Potential measurement of relativistic effects

In certain cases, with favourable orbital parameters, it is possible to measure the mass of both the pulsar and its companion (e.g. Demorest et al. 2010). When light passes near a massive body, the path that the light must travel is increased in length, due to the curvature of space–time caused by the massive body. This effect is known as Shapiro delay and may be measured for near edge-on binary systems containing an MSP. For low-eccentricity systems, the Shapiro delay, \( \Delta_{SB} \), at orbital phase \( \Phi \) is (e.g. Taylor 1992)

\[
\Delta_{SB} = -2r \ln[1 - s \sin \Phi],
\]

where \( r \) and \( s \) are post-Keplerian orbital parameters,

\[
r = \frac{Gm_s}{c^3} M_\odot, \quad (4)
\]

\[
s = \sin i \quad (5)
\]

for an orbit inclined at angle \( i \) to the observer with a companion of mass \( m_c \). Defining orbital phase \( \Phi = 0 \) to be at epoch of the ascending node, then the Shapiro delay is greatest at orbital phase \( \Phi = 0.25 \), when the pulsar is behind the companion, and allows both masses and the orbital inclination to be constrained where it can be measured.

The magnitude of the Shapiro delay is, however, extremely small (sub-\( \mu \)s) for all cases except where the orbital inclination is very close to 90°. As shown in Table 3, none of the timing residuals for these pulsars is currently below 5 \( \mu \)s, so the orbital inclination and the constituent masses cannot be constrained.

Another GR effect that has been observed for some pulsars is the advance of periastron, \( \dot{\omega} \). This is best measured for orbits with a well-defined eccentricity and angle of periastron, \( \omega \). Therefore, we only concern ourselves with PSR J1125–5825 and PSR J1708–3506 here. The value of \( \omega \) (Stairs et al. 2002) can be calculated, in rad s\(^{-1} \), by

\[
\dot{\omega} = 3 \left( \frac{GM_\odot}{c^3} \right)^{2/3} \left( \frac{P_s}{2\pi} \right)^{-5/3} \frac{1}{1 - e^2} (m_p + m_c)^{2/3} \quad (6)
\]

for a binary with eccentricity \( e \) and orbital period \( P_b \). The values of \( \dot{\omega} \) calculated for PSR J1125–5825 and PSR J1708–3506, assuming the median companion mass given in Table 3, are 2 \( \times 10^{-4} \) and 6 \( \times 10^{-5} \) deg yr\(^{-1} \), respectively. These values compare favourably with the measured \( \dot{\omega} = 2.5 \times 10^{-4} \) deg yr\(^{-1} \) of PSR J1903+0327 (Champion et al. 2008); however, this measurement was obtained with a timing rms of 1.9 \( \mu \)s and for a system with \( e = 0.44 \), which implies that any detection of \( \dot{\omega} \) is extremely improbable.

3 COMPARISON WITH DISCOVERIES FROM PREVIOUS SURVEYS AND PROSPECTS FOR MULTIWAVELENGTH DETECTION

3.1 Comparison with previous discoveries

Following the sensitivity curves presented in Keith et al. (2010), the left-hand panel of Fig. 3 plots the limiting sensitivity for the HTRU mid-latITUDE survey as a function of pulse period for pulsars at DMs of 50, 100 and 150 cm\(^{-3} \) pc, and also for the PMPS, responsible for the discovery of a large fraction of the previously known MSP population. Also plotted are each of the pulsars presented in this paper at their period and flux density. Due to the shorter observation time of the HTRU mid-latitude survey, the limiting flux density at long periods is higher than for the PMPS; however, the HTRU survey is more sensitive to pulsars with shorter rotational periods, due to the short sampling interval of 64 \( \mu \)s and the high frequency resolution of 0.39 MHz per channel (cf. 250 \( \mu \)s and 3 MHz for the PMPS). The right-hand panel of Fig. 3 demonstrates that as well as discovering short-period pulsars, the HTRU survey is sensitive to pulsars with a high DM. Our new discoveries occupy the

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Left-hand panel: minimum detectable flux density, for a detection with S/N = 8, for the HTRU survey (solid line) and the PMPS (dotted line). For each survey, this limiting flux density is plotted for DMs 50, 100 and 150 cm\(^{-3} \) pc from left to right, assuming the scattering law of Bhat et al. (2004). The circles indicate the approximate position of the newly discovered MSPs in this plane. Right-hand panel: the period and DM of all pulsars with \( P < 30 \) ms, excluding those in globular clusters. Squares indicate the position of our new discoveries in this plane.
short-period and high-DM region of the plot, which we can attribute to the short sampling time and narrow frequency channels of our survey system compared with previous blind searches for pulsars (see Keith et al. 2010, for a full discussion). Our survey is therefore, on average, finding shorter period MSPs than previous surveys, but are their companions any different? Recently, Bailes (2007) demonstrated that no recycled pulsars existed in which the minimum companion mass exceeds \((P/10\text{ ms}) M_\odot\). The only MSP to defy this relation was the newly discovered PSR J1903+0327 by Champion et al. (2008), which is thought to have had a peculiar history. All of our pulsars are in agreement with this empirical law.

In Fig. 4, we plot a histogram of the luminosity at 1.4 GHz of the previously known MSPs (where available, using \(P = 50\text{ ms}\) as an upper limit), taken from the pulsar catalogue (Manchester et al. 2005). A histogram of the luminosities of our discoveries, calculated using distances estimated by the Galactic electron distribution model of Cordes & Lazio (2002), is also plotted with shaded boxes. We have already shown that the HTRU survey is discovering pulsars of lower flux density, at higher DMs. Since DM is an approximate measure of the distance to a source, this implies that the discoveries have higher luminosities than many of the previously known population. This is borne out in our results – of the previously known MSPs with measured luminosities, \(\sim 60\) per cent have luminosities below 2 mJy kpc\(^2\). However, four of our newly discovered MSPs have a luminosity greater than 2 mJy kpc\(^2\). This trend is expected to continue with future discoveries, providing a more complete luminosity distribution in the known population.

### 3.2 The possibility of detection with *Fermi*

In the last year or so, about 30 MSPs have been discovered with radio follow-up of non-variable previously unidentified point sources from the *Fermi* Gamma-ray Space Telescope (Ray & Saz Parkinson 2010). These discoveries form a complementary group of MSPs to those likely to be found with the HTRU survey, since they are faint, but nearby sources. A check of the *Fermi* point source catalogue\(^1\) indicates that none of these newly discovered sources has yet been detected as gamma-ray sources, after 1 yr of observations (it is possible that with further observations *Fermi* may yet make a detection). Compared to pulsars which have been discovered from searches of *Fermi* point sources (Ransom et al. 2010), this lack of detection is consistent with sources which are more distant than the majority of the population. A useful metric with which we can compare the likelihood of a *Fermi* detection is by calculating \(\sqrt{E}/d^2\) (measured in erg kpc\(^{-2}\) s\(^{-1}\); see Abdo et al. 2010, for details). For the majority of *Fermi*-detected MSPs, \(\log(\sqrt{E}/d^2) \gtrsim 17.5\), and none has been detected where this value is \(< 16.5\). Of our discoveries, PSR J1125–5825 has the highest value of this metric, with \(\log(\sqrt{E}/d^2) = 16.6\). Therefore, it is unlikely *Fermi* will detect this pulsar, or any of our other discoveries, assuming the DM distance holds.

### 3.3 Potential for optical detection

In order to decide whether an optical detection of the companion will be possible for any of the NS–WD systems presented here, we must make use of WD evolutionary models to estimate the luminosity of the companions. Using WD cooling models as described in Fontaine, Brassard & Bergeron (2001), and using the characteristic age of the pulsar as an indication of the WD age, we are able to estimate the apparent magnitude of the companions, assuming the DM distance given by Cordes & Lazio (2002). These models are highly dependent upon the companion mass, but by using the minimum mass (see Table 3), we are able to put an upper limit on the brightness of the companion. Once we include the effects of interstellar reddening, it becomes unlikely that the companion will be visible, each having an apparent magnitudes greater than 30. This is a natural consequence of detecting sources at large distances in the Galactic plane.

### 4 THE ECLIPSING BINARY MSP

**PSR J1731–1847**

PSR J1731–1847 is an eclipsing binary system, and only the fourth to be published, following B1957+20, J2051–0827 and J1023+0038, to be found outside globular clusters. In order to understand the origin of the eclipsing material, we can approximate the radius of the companion’s Roche lobe, \(R_L\), as (Eggleton 1983)

\[
R_L = \frac{0.49a_{\text{eq}}^{2/3}}{0.6a_{\text{eq}}^{2/3} + \ln(1 + a^{1/3})} \sim 0.3 \, R_\odot.
\]

(7)

where \(q = m_c/m_p\) is the mass ratio of the binary system, and \(a\) is the separation of the pulsar from the companion. For this calculation, the companion’s mass was assumed to be the minimum possible given the mass function, and the pulsar mass was assumed to be 1.4 M\(_\odot\). In comparison, the radius of eclipse is approximately 0.9 R\(_\odot\), implying that much of the eclipse material is not gravitationally bound to the companion.

By studying the delay of pulses near to eclipse ingress and egress, we can infer properties of the material causing the eclipses. If we assume the delay, at observing frequency \(f\), to be purely dispersive, we can express it as a time delay, \(t\), relative to a wave of infinite frequency,

\[
t = \frac{e^2}{2\pi m_e c} \frac{\text{DM}}{f^2}.
\]

(8)

Hence, it is possible to attribute a DM to the delay and, using the orbital separation of the pulsar and its companion, infer the required density of free electrons to cause such a delay, assuming a homogeneous plasma.

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\(^1\) http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1yr_catalog/
We do not observe this amount of delay, and hence can discount the refractive eclipse model for PSR J1731−1847. Other eclipse mechanisms proposed by Thompson et al. which we disregard in this work are induced by Compton scattering and Raman scattering of the radio beam. When applied to PSR B1957+20, these models were found to be unviable when explaining eclipses at 1400 MHz, and so we do not explore them further.

Another eclipse mechanism put forward by Thompson et al. is pulse smearing due to the added electron density along the line of sight. The first TOA at eclipse egress is observed at 10 cm and is delayed by 450 μs. By equation (8), this implies an added DM of 0.98 cm−2 pc, which would cause the pulse to be smeared by 0.77 and 1.3 ms at 20 and 50 cm, respectively. This is significantly less than the pulse period of PSR J1731−1847, and yet the pulses are not visible; this indicates that pulse smearing is not wholly responsible for the eclipse.

Absorption of the radio emission by the eclipsing material is another potential mechanism for eclipses via two processes: (i) cyclotron absorption and (ii) synchrotron absorption. However, the optical depth of cyclotron absorption is noted by Thompson et al. to have a steep spectral index and may not be able to explain the total eclipses seen at 10 cm (see Fig. 5). Synchrotron absorption, on the other hand, has a shallower spectral index and may be able to explain these eclipses we observe in PSR J1731−1847 at 10 cm.

4.2 Comparison with other eclipsing systems

Including PSR J1731−1847, there are now 25 known eclipsing pulsars, many of which are found in globular clusters. Table 4 compares the eclipse properties of PSR J1731−1847 with those of four of the most well-studied eclipsing binary systems, PSR J1023+0038, PSR B1744−24A, PSR B1957+20 and PSR J2051−0827. All five of these eclipsing systems share similar eclipse and orbital parameters; however, PSR J1023+0038 and PSR J1748−2446A display anomalous eclipses indicative of gas outflow from the companion. PSR J1023+0038 displays only a very brief eclipse at ~3 GHz, in sharp contrast to the case of PSR J1731−1847. However, this is not unreasonable since the electron column density, N_e, in the orbital system of PSR J1023+0038 (calculated from the additional DM given in Archibald et al. 2009, shown in Table 4), is lower by a factor of ~6.5. Where N_e ~ 5 × 10^{17} cm^{-2} in the PSR J1731−1847 system, the residuals in the lower panel of Fig. 5 show almost no deviation from zero. It is noteworthy that N_e takes a similar value for each of these systems, which is not a requirement of any eclipse models.

The comparison of Ė/a^2 for these systems shows that the typical energy flux at the companion is around 10^{33} erg light-second^{-2} s^{-1}, more than an order of magnitude higher than the average for all

![Figure 5](https://academic.oup.com/mnras/article-abstract/416/4/2455/974277)

The bottom panel shows timing residuals for PSR J1731−1847 as a function of orbital phase at observing wavelengths of 10 (●), 20 (×) and 50 cm (+). The top panel shows the inferred electron density, from equation (8), for each TOA.

### Table 4. Eclipse properties for the pulsars PSR J1731−1847, PSR J1023+0038, PSR J1748−2446A, PSR B1957+20 and PSR J2051−0827.

| Parameter                  | J1731−1847 | J1023+0038 | J1748−2446A | B1957+20 | J2051−0827 |
|----------------------------|------------|------------|-------------|----------|------------|
| Eclipse radius (R_⊙)      | 0.9        | ~0.9       | 0.8         | 0.75     | 0.3        |
| Roche lobe radius (R_⊙)   | 0.3        | ~0.3       | 0.15        | 0.3      | 0.13       |
| P_b (d)                   | 0.311 134  | 0.198      | 0.075 646   | 0.382    | 0.0991     |
| |P_b| / P_b (s\(^{-1}\)) | 7 × 10^{-11} | 2.5 × 10^{-10} | ~       | 3.9 × 10^{-11} | 15.5 × 10^{-12} |
| |P_b| / P_b (s\(^{-1}\)) | 2.6 × 10^{-15} | 1.5 × 10^{-14} | ~       | 1.2 × 10^{-15} | 1.8 × 10^{-15} |
| E/\alpha^2 (erg light-second^{-2} s^{-1}) | 1.5 × 10^{33} | 3.8 × 10^{33} | ~       | 2.3 × 10^{33} | 4.8 × 10^{32} |
| N_e maximum (cm^{-2})     | 3 × 10^{18} | 4.6 × 10^{17} | 2 × 10^{18} | 4 × 10^{17} | 4 × 10^{17} |
| Anomalous eclipses        | No         | Yes        | Yes         | No       | No         |
binary systems. In the case that these ‘black widow’ systems really are ablating their companions, this shows some evidence for why this process does not occur in all binaries.

PSR B1957+20 and PSR J2051−0827 have both been demonstrated to show orbital period variations, with both a $P_b$ and a $P_a$. In the case of PSR B1957+20, these variations take place over a period of years, with $P_b = 1.5 \times 10^{-11}$ and $P_a = 1.4 \times 10^{-18}$ s$^{-1}$ (Arzoumanian, Fruchter & Taylor 1994). PSR J2051−0827 has a measured value for the $P_b$ of $6.4 \times 10^{-12}$, but this value has been observed to fluctuate over the 14 yr of observations; however, the variations are not smooth enough to allow measurement of a $P_a$ (Lazaridis et al. 2011). We do not expect, therefore, to be able to measure a $P_a$ for PSR J1731−1847 given that our data span less than a year. However, we have been able to obtain a tentative $P_b$ of $-7(2) \times 10^{-11}$.

The value of $|\dot{P}_b|/P_b$ in all these well-studied eclipsing systems are of the order of $10^{-15}$ s$^{-1}$. This gives an estimate of the lifetime of these systems of $\sim 10^3$ yr although the variation of $P_b$ in some of these systems indicates that this lifetime may not be too meaningful. From Fig. 1, it can be seen that PSR J1731−1847 has one of the highest $P$ of the eclipsing and binary pulsars.

5 DISCUSSION

The potential for optical detection of counterparts to these five new discoveries is not promising, due to the large distance and the associated Galactic extinction. Prospects for measurement of Shapiro delay are better although they are dependent upon the orbital inclination. If these systems are highly inclined, PSR J1125−5825 and PSR J1811−2405 will have Shapiro delays with the largest amplitude, potentially with as much as 20-μs delay. In the case of the 6.3-d orbit of PSR J1811−2405, this could be detectable, which would allow the measurement of the masses of the pulsar and its companion. For all but the highest inclination angles, however, the delay will not be observable with the current timing precision.

One of these pulsars, PSR J1731−1847, is in an eclipsing system with a companion of extremely low mass. Analysis of the eclipsing region shows that the pulse delay, if attributed to dispersion, implies an electron density similar to that measured for PSR B1744−24A and PSR B1957+20, which are also in eclipsing systems with low-mass companions.

Two of the pulsars have pulse profiles ideally suited for observations with a pulsar timing array. One of these is, however, PSR J1731−1847, for which there will likely be orbital period changes on time-scales of a year or more, and large DM variations that will render it unsuitable for use in pulsar timing arrays. As more observations are made of PSR J1811−2405, it will become clear how well precision timing can be performed with this pulsar, although the current rms is not small enough to merit inclusion in a timing array. The discovery of distant and bright MSPs is also important for a rounded view of the MSP population and their distribution in the Galaxy. This has implications for searches with future telescopes such as the Square Kilometer Array (SKA; Smits et al. 2009) and the Parkes Observatory which is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. SDB gratefully acknowledges the support of STFC in his PhD studentship. We thank Gemma Jansen for generously giving up some observing time and performing observations with the Westerbork telescope and Cees Bassa for useful discussions regarding the WD companions.

6 CONCLUSIONS

We present the discovery of five MSPs in the HTRU survey. These MSPs have short periods and DMS among the highest in the known population. One of the pulsars, PSR J1731−1847, displays regular eclipses in its 0.3-d orbit and, with a companion of minimum mass 0.04M⊙, appears to be a member of the ‘black widow’ group of MSPs.

The sensitivity to such objects can be attributed to the fast sampling rate and narrow filter bank channels of the hardware used for the HTRU survey.

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