The High Time Resolution Universe Pulsar Survey – XIII. PSR J1757−1854, the most accelerated binary pulsar

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ABSTRACT

We report the discovery of PSR J1757−1854, a 21.5-ms pulsar in a highly-eccentric, 4.4-h orbit with a neutron star (NS) companion. PSR J1757−1854 exhibits some of the most extreme relativistic parameters of any known pulsar, including the strongest relativistic effects due to gravitational-wave damping, with a merger time of 76 Myr. Following a 1.6-yr timing campaign, we have measured five post-Keplerian parameters, yielding the two component masses ($m_p = 1.3384(9)\,\mathrm{M_\odot}$ and $m_c = 1.3946(9)\,\mathrm{M_\odot}$) plus three tests of general relativity, which the theory passes. The larger mass of the NS companion provides important clues regarding the binary formation of PSR J1757−1854. With simulations suggesting 3-σ measurements of both the contribution of Lense–Thirring precession to the rate of change of the semimajor axis and the relativistic deformation of the orbit within ∼7–9 yr, PSR J1757−1854 stands out as a unique laboratory for new tests of gravitational theories.

Key words: gravitation – surveys – binaries: close – pulsars: individual: PSR J1757−1854.

1 INTRODUCTION

Since the discovery of the Hulse–Taylor pulsar (PSR B1913+16; Hulse & Taylor 1975), binary pulsars have played a critical role in providing key tests of general relativity (GR) and its alternatives. Even with the direct detection of gravitational waves (GWs;

Abbott et al. 2016) and the more recent direct observation of a double neutron star (DNS) merger (Abbott et al. 2017), binary pulsars are still able to provide some of the most important gravity tests with strongly self-gravitating bodies, particularly in the quasi-stationary strong-field gravity regime (Wex 2014). An example is the constraint on the leading-order GW emission in GR (as described by the quadrupole formula), for which the double pulsar (PSR J0737−3039; Burgay et al. 2003; Lyne et al. 2004) currently stands out as the most constraining system, surpassing LIGO by
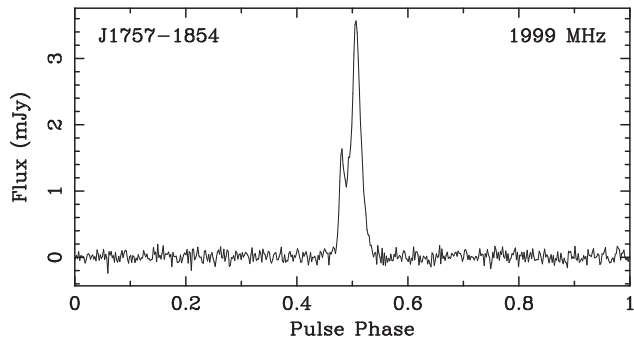
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Figure 1. Pulse profile of PSR J1757−1854, observed with the GBT on MJD 57857, integrated over approximately one full orbit.

three orders of magnitude (Abbott et al. 2016; Kramer 2016). PSR J0737−3039 currently offers five independent tests of GR [based on six post-Keplerian (PK) parameters and the mass ratio], of which it passes the most stringent to within a measurement uncertainty of only 0.05 per cent (Kramer et al. 2006; Breton et al. 2008). Other binary pulsars, such as the millisecond pulsar–white dwarf PSR J1738+0333, provide strong constraints on dipolar GW emission, a prediction of many alternative theories of gravity such as scalar–tensor theories (Freire et al. 2012).

Pulsar constraints on the nature of GWs, the limits of GR and on alternative gravitational theories are anticipated to provide both complementary and competitive tests against the most advanced ground-based GW detectors currently foreseen (Shao et al. 2017). However, this depends upon the discovery of additional relativistic systems capable of expanding the parameter space currently explored by binary pulsars. To this end, the High Time Resolution Universe South Low Latitude pulsar survey (HTRU-S LowLat, Keith et al. 2010; Ng et al. 2015), conducted using the Parkes 64-m radio telescope, was undertaken with the specific goal of discovering additional relativistic binary pulsars. This survey covers the inner Galactic plane ($-80° < l < 30°$ and $|b| < 3.5°$) and is the region predicted to contain the highest number of relativistic binaries (Belczynski, Kalogera & Bulik 2002).

Here, we report the discovery of PSR J1757−1854, the first relativistic binary discovered in the HTRU-S LowLat survey. PSR J1757−1854 (see Fig. 1) is a 21.5-ms pulsar in a 4.4-h orbit with an eccentricity of 0.61 and a NS companion, making the system a DNS. The compactness, high eccentricity and short orbital period of PSR J1757−1854 make it one of the most relativistic binary pulsars known, with the potential for even more rigorous constraints to be placed on GR and other gravitational theories.

2 DISCOVERY

2.1 Candidate identification and confirmation

To search for binary pulsars, we employ the 'time-domain resampling' technique (see e.g. Middleditch & Kristian 1984; Johnston & Kulkarni 1991), which assumes that the binary motion can be modelled as a constant line-of-sight acceleration. For a circular orbit, this assumption holds best when the quantity $r_b = t_{int}/P_b \leq 0.1$, where t_{int} is the integration time of the observation and P_b is the orbital period (see e.g. Johnston & Kulkarni 1991; Ng et al. 2015). Building on the technique of Eatough et al. (2013), our 'partially-coherent segmented acceleration search' uses this principle to blindly search for pulsars in compact binary systems by progressively halving each observation into smaller time segments

Table 1. Telescope front end and back end configurations, including the central frequency (f_c), bandwidth (Δf) of each combination and the number (n_{TOA}) and time span of the TOAs.

Receiver	Back end	$f_c (\Delta f)$ (MHz)	n_{TOA}	Span (MJD)
PKS:				
MB20	BPSR	1382(400)	9	57405−57406
	CASPSR[a]	1382(400)	41	57734−57986
H-OH	DFB4	1369(256)	57	57553−57675
	CASPSR[a]	1382(400)	55	57596−57635
JBO:				
L Band	ROACH[b]	1527(400)	422	57456−57958
EFF:				
7-Beam	FOLD	1360(240)	83	57573−57896
	BB[a]	1360(240)	84	57815−57986
GBT:				
PF1-800	GUPPI	820(200)	25	57620−57621
L-Band	GUPPI[a,b]	1499(800)	731	57795−57950
S-Band	GUPPI[a,b]	1999(800)	1655	57627−57998

Notes. [a]Observations recorded with coherent de-dispersion.
[b]Δf split into 200 MHz sub-bands before TOA production.

(as low as $t_{int} = 537$ s), which are independently searched (to accelerations as high as $|a| = 1200$ m s^{-2}). This has the trade-off of increasing our sensitivity to shorter orbital periods while gradually reducing our sensitivity in flux density. Full details of the technique are available in Ng et al. (2015).

PSR J1757−1854 was identified in the second 36-min half-length segment of a full 72-min observation recorded on MJD 56029, with an acceleration of -32 m s^{-2} and a signal-to-noise ratio (S/N) of 13.3. The pulsar's signal was recoverable across the full observation to a S/N of 21.4, but with a significantly changing acceleration (i.e. 'jerk'). Consequently, a time-domain acceleration search of the full-length observation detected only the pulsar at a reduced S/N of only 10.6, indicating that the segmented search greatly assisted in the discovery of this pulsar. At periastron, the pulsar reaches a maximum absolute acceleration of $\sim$684 m s^{-2}, the highest of any known binary pulsar system.

2.2 Non-detection in the PMPS

The Parkes Multibeam Pulsar Survey (PMPS, Manchester et al. 2001) contains a beam coincident with the timed position of PSR J1757−1854 (see Table 2). However, neither acceleration searches using both time-domain resampling and matched filtering (Ransom, Eikenberry & Middleditch 2002) nor a fold using the ephemeris in Table 2 detected the pulsar in the PMPS data. Based upon the radiometer equation (see e.g. Lorimer & Kramer 2005) and the dispersive smearing introduced by the 3-MHz channel size of the PMPS, we expect a S/N$_{PMPS} \simeq 8$, rendering any detection of PSR J1757−1854 difficult. Additional factors such as geodetic precession may also play a role, but at present a precise cause cannot be determined.

3 TIMING

3.1 Observations and data reduction

A summary of PSR J1757−1854's timing observations can be found in Table 1. Parkes (PKS) observations used the 21-cm multibeam

(MB20; Staveley-Smith et al. 1996) and H-OH receivers, in combination with the Berkeley Parkes Swinburne Recorder[1] (BPSR), the CASPER Parkes Swinburne Recorder[2] (CASPSR) and a Digital Filter Bank system (DFB4). Jodrell Bank (JBO) observations with the 76-m Lovell telescope employed an *L*-Band receiver with a ROACH backend system (Bassa et al. 2016). Observations at Effelsberg (EFF) were performed with the 7-Beam receiver with the PSRIX backend (Lazarus et al. 2016) operating in both a folded and baseband recording mode (FOLD and BB, respectively). Finally, observations with the Green Bank Telescope (GBT) were conducted using the *L*-Band, *S*-Band, and Prime-Focus 800-MHz (PF1-800) receivers, all in combination with the Green Bank Ultimate Pulsar Processing Instrument (GUPPI; DuPlain et al. 2008). All GBT and Effelsberg observations were designed to sample a full or significant fraction of the orbit.

Data reduction employed the DSPSR (van Straten & Bailes 2011), PSRCHIVE (Hotan, van Straten & Manchester 2004), SIGPROC[3], PRESTO (Ransom 2001), TEMPO,[4] and TEMPO2 (Hobbs, Edwards & Manchester 2006) software packages. Each TOA set was produced using its own reference profile (all rotated to the same pulse phase), and was weighted such that its reduced $\chi^2 = 1$. The data sets were combined using jumps fit across regions of common overlap. During this process, the pulsar's dispersion measure (DM) appeared to vary as a function of orbital phase. This resulted from an apparent inability of DSPSR and PSRCHIVE to correctly de-disperse across a large bandwidth during rapid orbital motion, despite this effect having been accounted for by TEMPO2's phase predictors (Hobbs et al. 2006). To counteract this, Jodrell Bank and GBT (*L* and *S* Band) TOAs were produced from 200-MHz sub-bands.

3.2 Measured parameters and implications

Our derived ephemeris of PSR J1757−1854, employing the DDH (Freire & Wex 2010) binary model, is provided in Table 2. Based upon the spin parameters, we derive a characteristic age $\tau_c \simeq 130\,\mathrm{Myr}$ and a surface magnetic field $B_{surf} \simeq 7.61 \times 10^9\,\mathrm{G}$, indicating that the pulsar has been partially recycled. Five PK parameters, including the rate of periastron advance $\dot{\omega}$, Einstein delay γ, orbital period derivative $\dot{P}_b$ and orthometric Shapiro parameters h_3 and ς, have been measured significantly. Using the DDGR model (Taylor 1987; Taylor & Weisberg 1989), which assumes the correctness of GR, we derive the total system mass $M = 2.73295(9)\,\mathrm{M}_\odot$ and the separate masses of the pulsar ($m_p = 1.3384(9)\,\mathrm{M}_\odot$) and its companion ($m_c = 1.3946(9)\,\mathrm{M}_\odot$). These masses, along with the high eccentricity and an implied second supernova (see Section 4) indicate that the system is a DNS. From m_p, m_c, and the mass function, we can further infer an inclination angle of $i = 84.0^{+0.4}_{-0.3}\,^\circ$ (or $96.0^{+0.3}_{-0.4}\,^\circ$, when accounting for the $i \leftrightarrow 180^\circ - i$ ambiguity of the mass function), i.e. the orbit appears to be close to edge-on.

Fig. 2 shows the constraints on the NS masses derived from the measured PK parameters under the assumption of GR. By using the intersection of $\dot{\omega}$ and γ to fix the two NS masses, we can derive three new tests of GR from the remaining PK parameters. Based upon the $\dot{\omega}$-γ mass solution, GR predicts an orbital decay due to GW damping of $\dot{P}_b = -5.2747(6) \times 10^{-12}$, which the measured value of $\dot{P}_b$ agrees with to within a relative uncertainty of only 5 per cent.

Table 2. Ephemeris of PSR J1757−1854, as derived using TEMPO2. Numbers in parentheses represent 1-σ uncertainties, with TOA errors re-weighted such that the reduced χ^2 went from 1.7 to 1.0. DM distances are derived from the NE2001 (Cordes & Lazio 2002) and YMW16 (Yao, Manchester & Wang 2017) models.

Right ascension, α (J2000)	17:57:03.78438(6)
Declination, δ (J2000)	−18:54:03.376(7)
Spin period, P (ms)	21.497231890027(7)
Spin period derivative, $\dot{P}$ (10^{-18})	2.6303(7)
Timing epoch (MJD)	57701
Dispersion measure, DM (pc cm^{-3})	378.203(2)
Binary model	DDH
Orbital period, P_b (d)	0.18353783587(5)
Eccentricity, e	0.6058142(10)
Projected semimajor axis, x (lt-s)	2.237805(5)
Epoch of periastron, T_0 (MJD)	57700.92599420(5)
Longitude of periastron, ω ($^\circ$)	279.3409(4)
Rate of periastron advance, $\dot{\omega}$ ($^\circ$ yr^{-1})	10.3651(2)
Einstein delay, γ (ms)	3.587(12)
Orbital period derivative, $\dot{P}_b$ (10^{-12})	−5.3(2)
Orthometric amplitude, h_3 (μs)	4.6(7)
Orthometric ratio, ς	0.90(3)
Mass function, f (M$_\odot$)	0.35718891(2)
Total system mass, M (M$_\odot$)	2.73295(9)[a]
Pulsar mass, m_p (M$_\odot$)	1.3384(9)[a]
Companion mass, m_c (M$_\odot$)	1.3946(9)[a]
Inclination angle, i ($^\circ$)	$84.0^{+0.4}_{-0.3}$ or $96.0^{+0.3}_{-0.4}$[a]
Flux density at 1.4 GHz, S_{1400} (mJy)	0.25(4)
DM distance, d (kpc)	7.4 (NE2001)
	19.6 (YMW16)
Surface magnetic field, B_{surf} (10^9 G)	7.61
Characteristic age, τ_c (Myr)	130
Spin-down luminosity, $\dot{E}$ (10^{30} ergs s^{-1})	10500
Time units	TCB
Solar system ephemeris	DE421
RMS residual (μs)	36

Note. [a]Parameters derived according to the DDGR model.

For ς and h_3, both observed values are within 1-σ agreement of their GR predicted values ($0.92^{+0.040}_{-0.025}$ and $5.37^{+0.72}_{-0.40}\,\mu$s, respectively), indicating that GR passes all three tests.

PSR J1757−1854 exceeds many of the relativistic qualities of previous binary pulsars, setting records (among others) for the closest binary separation at periastron (0.749 R$_\odot$) and the highest relative velocity (1060 km s^{-1}) at periastron. It also shows the strongest effects of GW damping yet seen in a relativistic pulsar binary, displaying the highest value of $\dot{P}_b$ as well as the highest value of $\dot{P}_b/P_b = -3.33 \times 10^{-16}\,$s^{-1}, the leading-order term in the cumulative shift in periastron time (see e.g. Taylor & Weisberg 1982). This results in an inferred merger time of 76 Myr. Hence, PSR J1757−1854 can be seen to probe a relativistic parameter space not yet explored by previous binary pulsars.

3.3 Searches for the companion NS

All GBT observations were recorded in coherently de-dispersed search mode, with two methods used to search for pulsations from the companion NS. The first method involved breaking each de-dispersed time series into ∼30-min segments, before performing a matched-filter acceleration search using the PRESTO program ACCELSEARCH with a filter width of $z_{max} = 50$ (where z is the
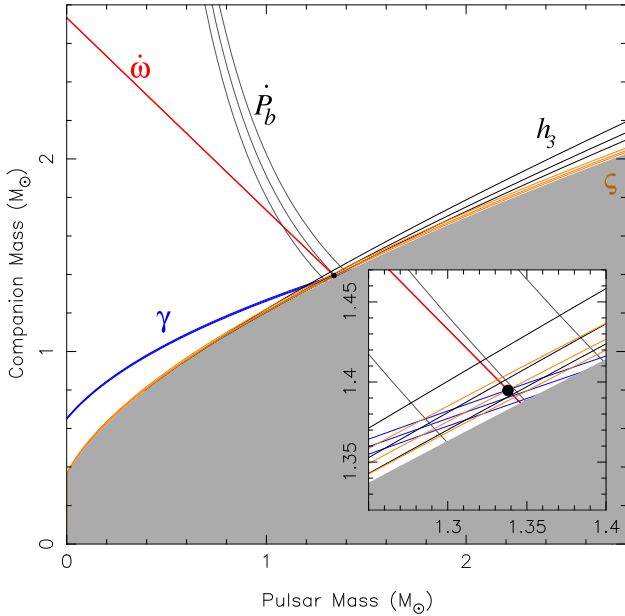
Figure 2. Mass-mass diagram for PSR J1757−1854. Shown are the mass constraints imposed under GR by each PK parameter, along with their 1-σ error bars. A zoomed view of the region of intersection is shown in the inset, with the black dot indicating the DDGR masses. The grey region is excluded by orbital geometry.

number of Fourier bins drifted by an accelerating pulsar). The second method (described in Martinez et al. 2015) involved re-sampling each time series in order to deconvolve the orbital motion of the companion NS as anticipated from the measured values of m_c and m_p, before applying a PRESTO-based periodicity search. Neither method detected pulsations from the companion. As precession may move the beam of the companion into the line-of-sight in the future, we will continue to record search-mode data so as to repeat these studies regularly.

4 EVOLUTIONARY HISTORY

PSR J1757−1854 is remarkable, given its combination of a short orbital period, a large eccentricity, a relatively massive young NS companion (more massive than the recycled pulsar, a property shared with only one other published DNS system, PSR B1534+12, Stairs et al. 2002), and a fast spinning recycled pulsar. The fast spin is expected for such a short orbital period DNS system, since in tight systems the recycling of the first-born NS is most efficient (see Case BB mass transfer modelling in Tauris, Langer & Podsiadlowski 2015; Tauris et al. 2017).

Both the large eccentricity and the relatively massive young NS hint that a large kick is likely to have been imparted on the young NS at birth; for example, the mass–kick correlation suggested by Tauris et al. (2017). Indeed the two DNS systems B1913+16 and B1534+12, which also have relatively massive young NS companions, were shown to have experienced kicks of ∼200−400 km s⁻¹.

To test this hypothesis for PSR J1757−1854, we performed Monte Carlo simulations of the kinematic effects of the second supernova following the method outlined in Tauris et al. (2017). As expected, we find that a large kick is most likely at work for this system (the broad distribution of solutions peaks at a value near 400 km s⁻¹). For the mass of the exploding star, we find solutions from less than 2 M⊙ and up to our maximum input limit of 7 M⊙.

However, the distribution peaks at the smallest value, supporting the idea of an ultra-stripped star exploding (Tauris et al. 2013, 2015).

5 FUTURE PROSPECTS

The simulations described in Section 4 also produce a systemic 3D velocity distribution for PSR J1757−1854, which peaks at a value of the order 200 km s⁻¹. Assuming a representative velocity in the plane of the sky of 150 km s⁻¹ and the NE2001 DM distance of 7.4-kpc (see Table 2) produces a predicted proper motion of 4.3 mas yr⁻¹. Furthermore, for the recycled pulsar, we also obtain a distribution of misalignment angles between the spin vector of the pulsar and the orbital angular momentum, with a median value of ∼25°.

Consequentially, PSR J1757−1854 is also expected to allow for future measurements of Lense–Thirring precession. Due to the large estimated distance to the pulsar, which suggests that we will not be able to correct for extrinsic acceleration effects sufficiently, we expect to be unable to employ the $\dot{\omega}$-$\dot{P}_b$ measurement technique used on PSR J0737−3039 (Kehl et al. 2016). However, the likelihood of a significant misalignment angle allows an alternate test using the contribution of Lense–Thirring precession to the rate of change of the projected semimajor axis, given by

$$\dot{x}_{LT} = x \cot i \left(\frac{\mathrm{d}i}{\mathrm{d}t} \right)_{LT}, \qquad (1)$$

where $(\mathrm{d}i/\mathrm{d}t)_{LT}$ is given by Equation (3.27) in Damour & Taylor (1992). Adopting a typically-assumed pulsar moment of inertia of $I = 1.2 \times 10^{45}$ g cm² (Lattimer & Schutz 2005) and neglecting the likely slower-spinning companion NS, we calculate that $|\dot{x}_{LT}|$ could be as large as 1.9×10^{-14} lt − s s⁻¹. Based upon a continuation of our current timing setup, and assuming additional MeerKAT observations consisting of one orbit/month commencing in mid-2018, we predict a future measurement of $\dot{x}_{LT}$ to within 3 σ in ∼8–9 yr. The corresponding (geodetic) spin precession of the pulsar (expected to be ∼3.1 ° yr⁻¹) is expected to cause changes in the pulse profile and polarization, which may allow a determination of the pulsar's spin orientation (see e.g. Kramer 1998).

PSR J1757−1854 is also an ideal system for measuring the PK parameter δ_θ, which describes the relativistic deformation of the elliptical orbit (Damour & Deruelle 1985). To date, δ_θ has been measured only in PSR B1913+16 (Weisberg & Huang 2016) and PSR J0737−3039 (Kramer et al., in preparation), in both cases with low significance. As described in Damour & Deruelle (1986), the timing residual contribution of δ_θ can be characterized by

$$\Delta_{\delta_\theta} \simeq -\delta_\theta \frac{e^2}{\sqrt{1 - e^2}} x \cos \omega \sin u, \qquad (2)$$

where u is the eccentric anomaly. The strong dependence of Δ_{δ_θ} on e implies that PSR J1757−1854 (along with other high-e relativistic binaries such as PSRs B1913+16 and B2127+11C) will show the strongest timing effects due to δ_θ. However, equation (2) also indicates that a measurement of δ_θ requires a significant change in ω in order to separate the residual effect of δ_θ from that of γ (for which $\Delta_\gamma = \gamma \sin u$). With its high $\dot{\omega} \simeq 10.37$ ° yr⁻¹, PSR J1757−1854 is therefore uniquely positioned to allow for a future measurement of δ_θ within a comparatively-short timeframe. Based on the same timing considerations as outlined for $\dot{x}_{LT}$, we predict a 3-σ measurement of δ_θ will be possible within ∼7–8 yr.

Finally, as noted in Section 3.2, PSR J1757−1854 has the largest observed $\dot{P}_b$ and the largest shift in periastron time due to GW emission of any known binary pulsar. This promises a further

high-precision test of GR's quadrupole formula for GW damping, as conducted previously with PSR B1913+16 (Weisberg & Huang 2016) and PSR J0737−3039 (Kramer et al. 2006; Kramer 2016). Timing simulations indicate a test precision of <1 per cent in only ~5 yr. Taking the Galactic potential of McMillan (2017) and our previous systemic velocity estimates, we anticipate that the uncertainties on the individual estimates of the distance to PSR J1757−1854 (see Cordes & Lazio 2002; Yao et al. 2017) will limit this test to within a few tenths of a per cent.

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