News and views regarding PSR J1757–1854, a highly-relativistic binary pulsar

A. D. Cameron* and M. Bailes

ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)
Centre for Astrophysics and Supercomputing, Swinburne University of Technology,
PO Box 218, Hawthorn VIC 3122, Australia
*E-mail: andrewcameron@swin.edu.au

V. Balakrishnan, D. J. Champion, P. C. C. Freire, M. Kramer and N. Wex

Max-Planck-Institut für Radioastronomie (MPIfR)
Auf dem Hügel 69, D-53121 Bonn, Germany

S. Johnston

Australia Telescope National Facility, CSIRO Space and Astronomy
PO Box 76, Epping NSW 1710, Australia

A. G. Lyne and B. W. Stappers

Jodrell Bank Center for Astrophysics, University of Manchester
Alan Turing Building, Oxford Road, Manchester M13 9PL, UK

M. A. McLaughlin, N. Pol and H. Wahl

Department of Physics and Astronomy, West Virginia University
PO Box 6315, Morgantown, WV 26506, USA

C. Ng

Dunlap Institute for Astronomy & Astrophysics, University of Toronto
50 St. George Street, Toronto, ON M5S 3H4, Canada

A. Possenti

Istituto Nazionale di Astrofisica (INAF), Osservatorio Astronomico di Cagliari
Via della Scienza 5, 09047 Selargius (CA), Italy

A. Ridolfi

Istituto Nazionale di Astrofisica (INAF), Osservatorio Astronomico di Cagliari
Via della Scienza 5, 09047 Selargius (CA), Italy

Max-Planck-Institut für Radioastronomie (MPIfR)
Auf dem Hügel 69, D-53121 Bonn, Germany

We provide an update on the ongoing monitoring and study of the highly-relativistic double neutron star binary system PSR J1757–1854, a 21.5-ms pulsar in a highly eccentric, 4.4-hour orbit. The extreme nature of this pulsar's orbit allows it to probe a parameter space largely unexplored by other relativistic binary pulsars. For example, it displays

one of the highest gravitational wave (GW) luminosities of any known binary pulsar, as well as the highest rate of orbital decay due to GW damping. PSR J1757–1854 is also notable in that it is an excellent candidate for exploring new tests of General Relativity and other gravitational theories, with possible measurements of both Lense-Thirring precession and relativistic orbital deformation (through the post-Keplerian parameter δ_θ) anticipated within the next 3–5 years.

Here we present a summary of the latest interim results from the ongoing monitoring of this pulsar as part of an international, multi-telescope campaign. This includes an update of the pulsar's long-term timing and post-Keplerian parameters, new constraints on the pulsar's proper motion and corresponding Shklovskii kinematic correction, and new limits on the pulsar's geodetic precession as determined by monitoring for secular changes in the pulse profile. We also highlight prospects for future work, including an updated timeline on new relativistic tests following the introduction of MeerKAT observations.

1. Introduction

For many decades, relativistic binary pulsars have been one of the key tools for studying different theories of gravity in the strong field regime, the current paradigm being Einstein's theory of General Relativity (GR). Discovered in 2016 as part of the HTRU-S Galactic Plane pulsar survey,[1,2] the 21.5-ms pulsar PSR J1757–1854 ranks as one of the most extreme examples of this class. Its high eccentricity ($e \simeq 0.606$) and compact orbit (measured via the projected semi-major axis, $x \simeq 2.24$ lt-s) around a neutron star companion combine some of the best properties of other notable relativistic binary pulsars, including the high eccentricity of PSR B1913+16[3] (the 7.75-hr orbital period *'Hulse-Taylor pulsar'*, with $e \simeq 0.617$) and the compact orbit of PSR J0737–3039A/B[4,5] (the 2.45-hr orbital period *'Double Pulsar'*, with $x \simeq 1.42$ lt-s). The extreme nature of PSR J1757–1854 is further demonstrated by multiple records set by the pulsar, including the highest acceleration ($\sim 700 \, \mathrm{m \, s^{-2}}$) and highest relative velocity ($\sim 1000 \, \mathrm{km \, s^{-1}}$) seen in a binary pulsar, as well as the highest rate of orbital decay due to gravitational wave damping and one of the shortest predicted merger times of any Galactic double neutron star system ($\sim 76 \, \mathrm{Myr}$). Together, these properties make PSR J1757–1854 a highly promising candidate for providing new insights into theories of gravity.

Here, we describe some of the ongoing aspects of the work involving this pulsar, in advance of a more detailed peer-reviewed publication anticipated by mid-2022.

2. Current timing and post-Keplerian tests

Since its discovery in 2016, PSR J1757–1854 has been observed by multiple radio telescopes as part of an international collaboration, including the Parkes[a] (Australia), Effelsberg (Germany), Lovell (UK), Green Bank (GBT; USA) and MeerKAT (South Africa) telescopes. This data was analysed using a standard pulsar timing

---

[a]Also known by its indigenous Wiradjuri name *'Murriyang'*.

technique,[6] wherein summed, average pulse profiles are cross-correlated against high signal-to-noise (S/N) template profiles to produce a dataset of high-precision pulse 'times of arrival' (TOAs). Each TOA represents the mean arrival time of an integrated pulse profile from the pulsar. These are then iteratively fit using a *timing ephemeris* in order to develop a high-precision model of the pulsar's behaviour.

Currently, the GBT accounts for the overwhelming majority of PSR J1757–1854's TOAs, having produced over 22,000 TOAs since it began observing in mid-2016. Data from the GBT is recorded in a full-Stokes coherent search mode at both L and S-bands (800 MHz bandwidth centered at 1500 and 2000 MHz respectively). We currently record one 4.4-hr orbit at each frequency every two months.

Table 1. Latest timing parameters for PSR J1757–1854, based on data from the GBT and Parkes between MJD 57405–59363 and employing the DDH[7] binary model. Values in parentheses give the 1-σ uncertainties on the final digit.

Astrometric & spin parameters	
Right ascension, α (J2000)............	17:57:03.78412(2)
Declination, δ (J2000)	-18:54:03.359(4)
Spin period, P (ms)	21.4972318900292(6)
Spin period derivative, $\dot{P}$	$2.627335(9) \times 10^{-18}$
Dispersion measure (pc cm^{-3})........	378.203(2)
Proper motion in RA, μ_α (mas yr^{-1}).	$-4.36(12)$
Proper motion in DEC, μ_δ (mas yr^{-1})	$-0.8(14)$
Period and position epoch (MJD)	57701
Orbital parameters	
Orbital period, $P_{\rm b}$ (d)	0.183537835854(7)
Eccentricity, e	0.6058171(3)
Projected semimajor axis, x (lt-s).....	2.2378060(15)
Epoch of periastron, T_0 (MJD)	57700.92599421(3)
Longitude of periastron, ω (°)	279.34090(9)
Post-Keplerian parameters	
Rate of periastron advance, $\dot{\omega}$ (° yr^{-1})	10.36498(3)
Einstein delay, γ (ms)	3.5891(16)
Orbital period derivative, $\dot{P}_{\rm b}$	$-5.294(6) \times 10^{-12}$
Orthometric amplitude, h_3 (μs).......	5.08(18)
Orthometric ratio, ς	0.899(10)
Mass measurements (based on $\dot{\omega}$ and γ)	
Pulsar mass, $m_{\rm p}$ (M$_\odot$)	1.3406(5)
Companion mass, $m_{\rm c}$ (M$_\odot$)	1.3922(5)
Inclination angle, i (°)................	85.0(2)

The most recent timing ephemeris for PSR J1757–1854 is given in Table 1. This includes five theory-independent post-Keplerian (PK) relativistic parameters, from which we can derive three independent tests of gravity. A mass-mass diagram showing the mass constraints imposed by each PK parameter under GR is shown

in Figure 1. By fixing a solution for the masses of the pulsar and the companion neutron star using the intersection of $\dot{\omega}$ and γ (the most precisely measured PK parameters), the further intersection of each remaining PK parameter provides one additional test of consistency. Both the orthometric amplitude and ratio parameters of the Shapiro delay[7] (h_3 and ς) are consistent to within 3.7% and 1.9% of their GR-predicted values respectively, and are approximately consistent with the $\dot{\omega} - \gamma$ intersection. However, although the observed value of the orbital period derivative $\dot{P}_b$ is also consistent with GR to within at least 1%, its location on the mass-mass diagram is inconsistent with the constraints set by $\dot{\omega}$ and γ under the assumption of GR being correct. This is further discussed in Section 2.1.
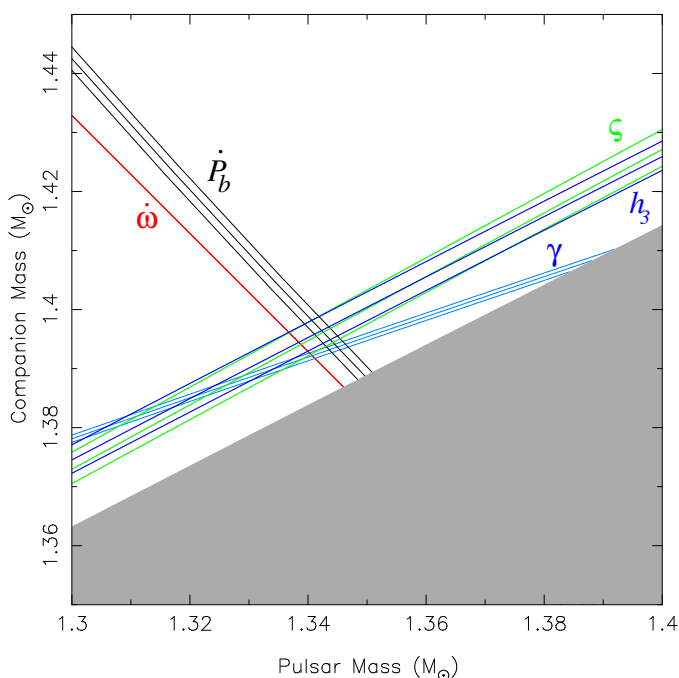

Fig. 1.   Mass-mass diagram for PSR J1757–1854. Each coloured triplet of lines shows the constraints (with 1-σ uncertainty) placed by each of the measured PK parameters in Table 1 on the mass of the pulsar and the companion neutron star, in this case according to GR. The measured uncertainty of $\dot{\omega}$ is so small that it cannot be seen at this scale. The grey region in the bottom right is excluded due to orbital geometry.

2.1. *Proper motion and the radiative test of gravity*

A recent development in the timing of PSR J1757–1854 has been the first constrained measurement of the pulsar's proper motion, which is also listed in Table 1. The component in right ascension (μ_α) is detectable at approximately $36\,\sigma$, while the component in declination (μ_δ) remains poorly constrained, although its contribution

to the total proper motion remains small given its value relative to μ_α. Together, these values indicate a total proper motion of

$$\mu_{\mathrm{T}} = \sqrt{\mu_\alpha^2 + \mu_\delta^2} = 4.4\,(3)\ \mathrm{mas\,yr^{-1}}. \tag{1}$$

This allows us to attempt to quantify the contributions contaminating the observed value of the orbital period derivative, $\dot{P}_{\mathrm{b,obs}}$. We define the excess contribution as

$$\dot{P}_{\mathrm{b,exs}} = \dot{P}_{\mathrm{b,obs}} - \left(\dot{P}_{\mathrm{b,GR}} + \dot{P}_{\mathrm{b,Gal}} + \dot{P}_{\mathrm{b,Shk}} \right), \tag{2}$$

where $\dot{P}_{\mathrm{b,GR}}$ is the expected intrinsic contribution from GR (here calculated using the mass values derived from the observed $\dot{\omega}$ and γ as given in Table 1); $\dot{P}_{\mathrm{b,Gal}}$ is the contribution from the acceleration of the pulsar within the Galactic potential[8] (dependent on position, distance and the chosen model of the Galactic potential); and $\dot{P}_{\mathrm{b,Shk}}$ is the contribution from the Shklovskii effect[9] (dependent on distance and proper motion).
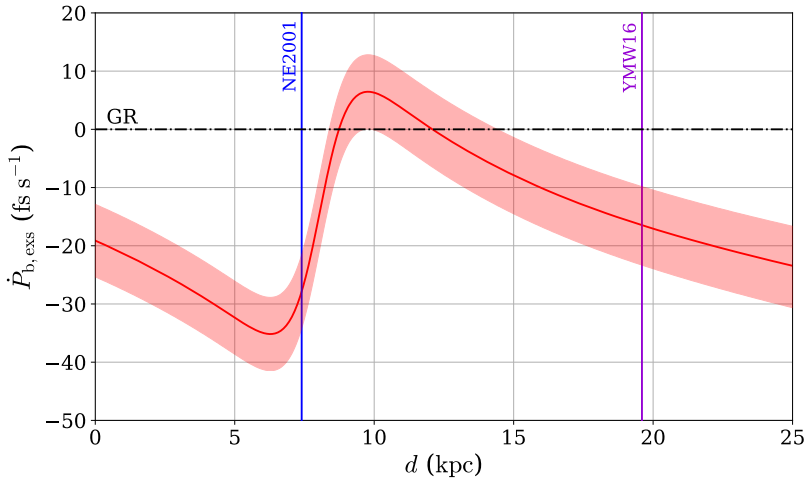

Fig. 2.   The excess contribution to the orbital period derivative $\dot{P}_{\mathrm{b,exs}}$ as calculated by Equation 2, plotted (red) as a function of distance. The shaded region shows the 1-σ uncertainty. $\dot{P}_{\mathrm{b,Gal}}$ was calculated using the McMillan Galactic potential.[10] The vertical blue (left) and magenta (right) lines indicate the NE2001[11] and YWM16[12] DM-distance estimates respectively. The horizontal dashed black line shows the GR expectation of $\dot{P}_{\mathrm{b,exs}} = 0$.

For the radiative $\dot{P}_{\mathrm{b}}$ test of GR to be considered 'passed', $\dot{P}_{\mathrm{b,exs}}$ must be consistent with zero, given that the other contributions have been accurately accounted for. However, although we have now quantified the pulsar's proper motion, we still lack an accurate estimate of the pulsar's distance. This is demonstrated in Figure 2, where we show how $\dot{P}_{\mathrm{b,exs}}$ depends on the distance to PSR J1757–1854.

Assuming GR, the distance to PSR J1757–1854 should fall between approximately 8.5–14.5 kpc. Therefore, available distance estimates based on the pulsar's dispersion measure (DM), including both the NE2001[11] (7.4 kpc) and the YMW16[12] (19.6 kpc) electron density models, are currently excluded. This is also shown in Figure 2. However, we note that these DM-distance estimates typically come with large uncertainties,[13] making a definitive determination difficult. Additionally, the McMillan Galactic potential model[10] we have used in our analysis has known shortcomings at distances of approximately 7–9 kpc in the central regions of the Galaxy near PSR J1757–1854's position, further complicating this assessment.

Without an accurate distance to PSR J1757–1854, the utility of the radiative test of gravity is unfortunately limited. As seen in Figure 2, the unknown distance introduces an approximate uncertainty to $\dot{P}_{\text{b,exs}}$ of at least $\pm 20 \times 10^{-15}$, more than three times the current uncertainty of $\dot{P}_{\text{b,obs}} = 6 \times 10^{-15}$, such that the precision of the radiative test of GR is limited to about $0.4\,\%$. We are currently exploring ways of further refining the estimated distance to PSR J1757–1854 (e.g. through VLBI astrometry). However, by assuming GR, we will still be able to inform our understanding of the pulsar's evolution. For example, the currently allowed distance range indicates a transverse velocity based on μ_{T} between 180–300 km s^{-1}, well in agreement with simulations of the neutron star kick associated with the second progenitor supernova.[2]

3. Attempts to detect the presence of geodetic precession

Our current understanding of the binary evolution of PSR J1757–1854 suggests the strong likelihood of a misalignment between the pulsar's spin vector and the orbital angular momentum vector.[2] As a result, we anticipate the presence of geodetic precession at a rate of $\Omega_{\text{geod}} \simeq 3.07\,^{\circ}\,\deg\,\text{yr}^{-1}$, which if detected may serve as another test of GR. We have therefore analysed the current GBT dataset for evidence of changes in the pulse profile, which would indicate a changing line-of-sight through the emission cone of the pulsar as expected from geodetic precession.[14]

Our method adapts an approach previously applied[15] to PSR J1022+1001. Each GBT observation (at both L and S-bands) spanning greater than 80% the orbital period is summed in time, frequency and polarisation before being fit by a template composed of three component Gaussian curves. We then normally re-sample each profile bin using the off-pulse root-mean-squared noise value to generate at least 1,000 randomly 're-noised' profiles, to which the template is re-fit. From each new fitted template, the positions and amplitudes of the major and minor peaks are then measured, as well as the intercept positions at 10% and 50% of the profile's maximum amplitude. The mean and standard deviation of each parameter's statistical distribution across all fitted templates are then taken as the nominal value and its uncertainty.

This approach has for the first time confirmed the presence of statistically significant profile change. An example of this is given in Figure 3, which shows that
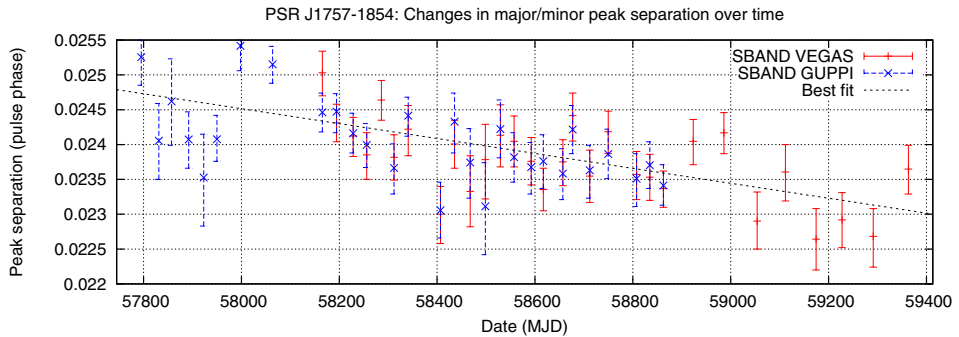
Fig. 3.   Change in phase separation of the major and minor peaks of PSR J1757–1854's pulse profile, as measured by the GBT at S-band using the GUPPI and VEGAS backends. The line of best fit corresponds to a decreasing separation of $0.14\,(2)\,^{\circ}\,\mathrm{yr}^{-1}$.

the separation between the two peaks of PSR J1757–1854's profile (termed the 'major' and 'minor' peaks) is decreasing (i.e. moving closer together) by an average rate of approximately $0.14\,(2)\,^{\circ}\,\mathrm{yr}^{-1}$. The width of the profile at both 10% and 50% also appears to be shrinking at a commensurate rate, with all trends most pronounced at S-Band due to the decreased influence of scattering (with respect to lower-frequency L-band observations). The precise physical implications of these changes are to be explored in a future publication, but their detection provides fundamental evidence for the presence of geodetic precession, as well as evidence for the suspected spin/orbit misalignment present in the binary system.

4. Searches for the companion neutron star

If PSR J1757–1854's neutron star companion was confirmed to be an active radio pulsar, it would immensely enhance the scientific utility of this pulsar and its binary system. This is most obviously demonstrated by the prior example of the Double Pulsar, where the presence of the second pulsar PSR J0737–3039B allowed additional tests of gravity beyond those normally available, including the detection of geodetic precession[16] and an independent determination of the mass ratio.[17]

We have therefore conducted an ongoing search for evidence of pulsations from the neutron star companion to PSR J1757–1854. This search has focused on observations from the GBT, which are recorded in a coherently-dedispersed search mode so as to allow for optimal search sensitivity across all pulse periods. Given our precise knowledge of PSR J1757–1854's orbit as detailed in Table 1, each observation is re-sampled using the inferred orbit of the companion via the custom software package PYSOLATOR.[18] This allows the companion to appear stationary such that any pulsations would appear as a single narrow peak in a resulting Fourier spectrum. To account for the small degree of uncertainty in the companion orbit, different

re-sampled trials are produced using values of the mass ratio $q = m_{\rm p}/m_{\rm c}$ between $0.9554 < q < 0.9661$ in increments of 0.00005. The resulting Fourier power spectra from each observation are then stacked and summed, boosting the total S/N of any pulsations.

To date, this search has unfortunately returned negative results, although the complete GBT dataset has yet to be analysed. In total, approximately 389.7 hr of GBT observations are currently on file, although there is significant overlap in this dataset between the VEGAS and GUPPI backends during intervals when both were recorded simultaneously. Ongoing searches for the companion neutron star will continue, as the companion may become detectable in the event that it precesses into view in the near future, given the expected precession rate of $\Omega_{\rm geod} \simeq 2.97\,^\circ\,{\rm deg\,yr}^{-1}$.

5. Future observations and anticipated tests of gravity

5.1. *Addition of MeerKAT*

Although observations with South Africa's MeerKAT telescope have been ongoing since 2019 as part of the MeerTIME program,[19] all these observations took place with MeerKAT's L-band receiver, which has a large 856 MHz bandwidth centered at 1283.5 MHz. This frequency band is located at lower frequencies than those of the GBT L-band receiver and therefore is much more susceptible to pulse broadening via scattering than the GBT L-band.[20] As a consequence, even though MeerKAT can achieve about twice the S/N of the GBT for this target, the available timing precision from both telescopes is roughly equivalent.

These effects are expected to be mitigated as part of the ongoing rollout of a fleet of MeerKAT S-band receivers (with a bandwidth of approximately 1750 MHz centred at 2625 MHz), designed by the MPIfR. The decreased influence of scattering at these higher frequencies combined with the wider bandwidth and the pulsar's relatively flat spectral index suggest an improvement in TOA precision to within 10 μs or better (compared with a typical TOA precision of 25–30 μs currently achievable using similar TOA integration times with the current GBT and MeerKAT receivers). This will provide a significant advantage in the ongoing timing of the pulsar.

5.2. *Future tests of gravity*

PSR J1757–1854 is expected to provide new insight into two rarely-explored tests of gravity within the next few years. The first of these is the *relativistic orbital deformation*, characterised by the PK parameter δ_θ, which describes the deviation of the orbit from a pure Keplerian ellipse due to the effects of relativity. The measurability of δ_θ scales with both eccentricity and $\dot\omega$, positioning PSR J1757–1854 as an ideal system for providing constraint in the short-term. Meanwhile, the Hulse-Taylor pulsar[21] (lower $\dot\omega$) and the Double Pulsar (lower eccentricity) have to date only weakly constrained δ_θ despite having been studied for far longer.

The second anticipated test involves the detection of Lense-Thirring precession, which to date has not been detected in a double neutron star binary system. We intend to detect this effect via the measurement of a change in the semi-major axis,[22] $\dot{x}_{\mathrm{LT}}$. Although in general $\dot{x}_{\mathrm{LT}}$ becomes negligible for small misalignment angles between the pulsar spin and orbital angular momentum vectors, our recent detection of geodetic precession confirms that a significant misalignment is likely. The Lense-Thirring effect is also proportional to the neutron star moment of inertia; should the Lense-Thirring effect be detected here, it would lead to a rare measurement of this quantity and thereby provide insight into the neutron star equation of state.

The timescale over which each of these parameters is anticipated to be constrained was determined by a simulation of the anticipated timing campaigns. A simulation was produced by extrapolating the current GBT timing campaign until the end of 2024, and including an equivalent MeerKAT S-band campaign comprising one full orbit recorded every two months, starting in 2022. Timing ephemerides were fit to the data at set intervals, while averaging the results of 30 realisations of the dataset. Based on these simulations, we anticipate the achievement of a 3-σ constraint of δ_θ between approximately 2024–2025, and of $\dot{x}_{\mathrm{LT}}$ between 2025–2026.

Acknowledgments

References

1. M. J. Keith, A. Jameson, W. van Straten, M. Bailes, S. Johnston, M. Kramer, A. Possenti, S. D. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, N. D'Amico, L. Levin, P. L. McMahon, S. Milia and B. W. Stappers, The High Time Resolution Universe Pulsar Survey - I. System configuration and initial discoveries, *Monthly Notices of the Royal Astronomical Society* **409**, 619 (December 2010).

2. A. D. Cameron, D. J. Champion, M. Kramer, M. Bailes, E. D. Barr, C. G. Bassa, S. Bhandari, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, R. P. Eatough, C. M. L. Flynn, P. C. C. Freire, A. Jameson, S. Johnston, R. Karuppusamy, M. J. Keith, L. Levin, D. R. Lorimer, A. G. Lyne, M. A. McLaughlin, C. Ng, E. Petroff, A. Possenti, A. Ridolfi, B. W. Stappers, W. van Straten, T. M. Tauris, C. Tiburzi and N. Wex, The High Time Resolution Universe Pulsar Survey - XIII. PSR J1757-1854, the most accelerated binary pulsar, *Monthly Notices of the Royal Astronomical Society* **475**, L57 (March 2018).

3. R. A. Hulse and J. H. Taylor, Discovery of a pulsar in a binary system, *Astrophysical Journal* **195**, L51 (January 1975).

4. M. Burgay, N. D'Amico, A. Possenti, R. N. Manchester, A. G. Lyne, B. C. Joshi, M. A. McLaughlin, M. Kramer, J. M. Sarkissian, F. Camilo, V. Kalogera, C. Kim and D. R. Lorimer, An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system, *Nature* **426**, 531 (December 2003).

5. A. G. Lyne, M. Burgay, M. Kramer, A. Possenti, R. N. Manchester, F. Camilo, M. A. McLaughlin, D. R. Lorimer, N. D'Amico, B. C. Joshi, J. Reynolds and P. C. C. Freire, A Double-Pulsar System: A Rare Laboratory for Relativistic Gravity and Plasma Physics, *Science* **303**, 1153 (February 2004).

6. D. R. Lorimer and M. Kramer, *Handbook of Pulsar Astronomy* (Cambridge Univ. Press, Cambridge, 2005).

7. P. C. C. Freire and N. Wex, The orthometric parametrization of the Shapiro delay and an improved test of general relativity with binary pulsars, *Monthly Notices of the Royal Astronomical Society* **409**, 199 (November 2010).

8. T. Damour and J. H. Taylor, On the Orbital Period Change of the Binary Pulsar PSR 1913+16, *Astrophysical Journal* **366**, p. 501 (January 1991).

9. I. S. Shklovskii, Possible Causes of the Secular Increase in Pulsar Periods, *Soviet Astronomy* **13**, p. 562 (feb 1970).

10. P. J. McMillan, The mass distribution and gravitational potential of the Milky Way, *Monthly Notices of the Royal Astronomical Society* **465**, 76 (February 2017).

11. J. M. Cordes and T. J. W. Lazio, NE2001.I. A New Model for the Galactic Distribution of Free Electrons and its Fluctuations, *arXiv e-prints* (July 2002).

12. J. M. Yao, R. N. Manchester and N. Wang, A New Electron-density Model for Estimation of Pulsar and FRB Distances, *Astrophysical Journal* **835**, p. 29 (January 2017).

13. A. D. Cameron, D. J. Champion, M. Bailes, V. Balakrishnan, E. D. Barr, C. G. Bassa, S. Bates, S. Bhandari, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, C. M. L. Flynn, A. Jameson, S. Johnston, M. J. Keith, M. Kramer, L. Levin, A. G. Lyne, C. Ng, E. Petroff, A. Possenti, D. A. Smith, B. W. Stappers, W. van Straten, C. Tiburzi and J. Wu, The High Time Resolution Universe Pulsar Survey - XVI. Discovery and timing of 40 pulsars from the southern Galactic plane, *Monthly Notices of the Royal Astronomical Society* **493**, 1063 (March 2020).

14. M. Bailes, Geodetic precession in binary pulsars, *Astronomy and Astrophysics* **202**, 109 (August 1988).

15. P. V. Padmanabh, E. D. Barr, D. J. Champion, R. Karuppusamy, M. Kramer, A. Jessner and P. Lazarus, Revisiting profile instability of PSR J1022+1001, *Monthly Notices of the Royal Astronomical Society* **500**, 1178 (January 2021).

16. R. P. Breton, V. M. Kaspi, M. Kramer, M. A. McLaughlin, M. Lyutikov, S. M. Ransom, I. H. Stairs, R. D. Ferdman, F. Camilo and A. Possenti, Relativistic Spin Precession in the Double Pulsar, *Science* **321**, p. 104 (July 2008).

17. M. Kramer, I. H. Stairs, R. N. Manchester, M. A. McLaughlin, A. G. Lyne, R. D. Ferdman, M. Burgay, D. R. Lorimer, A. Possenti, N. D'Amico, J. M. Sarkissian, G. B. Hobbs, J. E. Reynolds, P. C. C. Freire and F. Camilo, Tests of General Relativity from Timing the Double Pulsar, *Science* **314**, 97 (October 2006).

18. A. Ridolfi, PYSOLATOR: Remove orbital modulation from a binary pulsar and/or its companion (March 2020).

19. M. Bailes, A. Jameson, F. Abbate, E. D. Barr, N. D. R. Bhat, L. Bondonneau, M. Burgay, S. J. Buchner, F. Camilo, D. J. Champion, I. Cognard, P. B. Demorest, P. C. C. Freire, T. Gautam, M. Geyer, J. M. Griessmeier, L. Guillemot, H. Hu, F. Jankowski, S. Johnston, A. Karastergiou, R. Karuppusamy, D. Kaur, M. J. Keith, M. Kramer, J. van Leeuwen, M. E. Lower, Y. Maan, M. A. McLaughlin, B. W. Meyers, S. Osłowski, L. S. Oswald, A. Parthasarathy, T. Pennucci, B. Posselt, A. Possenti, S. M. Ransom, D. J. Reardon, A. Ridolfi, C. T. G. Schollar, M. Serylak, G. Shaifullah, M. Shamohammadi, R. M. Shannon, C. Sobey, X. Song, R. Spiewak, I. H. Stairs, B. W. Stappers, W. van Straten, A. Szary, G. Theureau, V. Venkatraman Krishnan, P. Weltevrede, N. Wex, T. D. Abbott, G. B. Adams, J. P. Burger, R. R. G. Gamatham, M. Gouws, D. M. Horn, B. Hugo, A. F. Joubert, J. R. Manley, K. McAlpine, S. S. Passmoor, A. Peens-Hough, Z. R. Ramudzuli, A. Rust, S. Salie, L. C. Schwardt, R. Siebrits, G. Van Tonder, V. Van Tonder and M. G. Welz, The MeerKAT telescope as a pulsar facility: System verification and early science results from MeerTime, *Publications of the Astronomical Society of Australia* **37**, p. e028 (July 2020).

20. M. Kramer, I. H. Stairs, V. Venkatraman Krishnan, P. C. C. Freire, F. Abbate, M. Bailes, M. Burgay, S. Buchner, D. J. Champion, I. Cognard, T. Gautam, M. Geyer, L. Guillemot, H. Hu, G. Janssen, M. E. Lower, A. Parthasarathy, A. Possenti, S. Ransom, D. J. Reardon, A. Ridolfi, M. Serylak, R. M. Shannon, R. Spiewak, G. Theureau, W. van Straten, N. Wex, L. S. Oswald, B. Posselt, C. Sobey, E. D. Barr, F. Camilo, B. Hugo, A. Jameson, S. Johnston, A. Karastergiou, M. Keith and S. Osłowski, The relativistic binary programme on MeerKAT: science objectives and first results, *Monthly Notices of the Royal Astronomical Society* **504**, 2094 (June 2021).

21. J. M. Weisberg and Y. Huang, Relativistic Measurements from Timing the Binary Pulsar PSR B1913+16, *Astrophysical Journal* **829**, p. 55 (September 2016).

22. T. Damour and J. H. Taylor, Strong-field tests of relativistic gravity and binary pulsars, *Physical Review D (Particles, Fields, Gravitation, and Cosmology)* **45**, 1840 (March 1992).