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Strong-field tests of gravity with the double pulsar

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This first-ever double-pulsar system was discovered in 2003, consisting of two visible pulsars which orbit the common centre of mass in a slightly eccentric orbit in only 2.4 hours. One of the pulsars appears to be old and recycled with a spin period of only 22 ms. Its companion is younger and rotating slower with a period of 2.8 s, confirming the long-proposed recycling theory for millisecond pulsars. The system provides an exciting opportunity to study the workings of pulsar magnetospheres and represents a truly unique laboratory for relativistic gravitational physics. Both aspects are greatly facilitated by the very fortunate fact that the orbit is seen nearly perfectly edge on. This alignment allows the detection of the Shapiro delay in the pulse arrival times of the 22-ms pulsar when its pulses propagate through the curved space-time near the slowly rotating pulsar. In addition to updating on the continuing observations, this contribution introduces a new timing model that represents a variation of Damour-Deruelle (1986) for highly inclined orbits.

1 Introduction

To date the theory of general relativity (GR) has passed all observational tests with flying colours. Nevertheless, GR may not be the last word in our understanding of gravitational physics, and it is important to experimentally confront the theory with new observations to explore different aspects and/or achieve higher precision. While some of the most stringent tests of GR are obtained by satellite experiments in the solar system, these solar-system experiments are all made in the weak-field gravitational regime. Tests of the strong-field limit, in particular involving the radiative aspects of GR, need also to be tested. For instance, it is possible to construct theories, which would pass all solar-system tests but would show deviations from GR in the strong-field limit (see e.g. [1]). Precision tests in the strong-field regime are best achieved by observing radio pulsars.

Pulsars, highly magnetised rotating neutron stars, are unique and versatile objects which can be used to study an extremely wide range of physical and astrophysical problems. Some of the best known applications are studies of gravitational physics. We report on some aspects of such studies made possible by the first ever discovered double pulsar [2, 3] which represents a truly unique laboratory for relativistic gravity. In addition to a brief update on the continued observations of this pulsar, we will introduce a new timing model that was developed by paying particular attention to the situation found in the double pulsar and its

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highly inclined orbit. A complete and more up-to-date report of the timing results will be shortly presented elsewhere (Kramer et al. in prep.).

2 The double pulsar

Our team discovered the 22.8-ms pulsar J0737−3039 in April 2003 [2] in an extension to the hugely successful Parkes Multi-beam survey [4]. It was soon found to be a member of the most extreme relativistic binary system ever discovered: its short orbital period ($P_b = 2.4$ hrs) is combined with a remarkably high value of periastron advance ($\dot{\omega} = 16.9\,\mathrm{deg}\ \mathrm{yr}^{-1}$, i.e. four times larger than for the first binary pulsar PSR B1913+16). This large precession of the orbit was measurable after only a few days of observations. The system parameters predict that the two members of the binary system will coalesce on a short time scale of only ~ 85 Myr. This boosts the hopes for detecting a merger of two neutron stars with first-generation ground-based gravitational wave detectors by a factor of 5-10 compared to previous estimates based on only the double neutron stars B1534+12 and B1913+16 [2,5].

In October 2003, we detected radio pulses from the second neutron star [3]. The reason why signals from the 2.8-s pulsar companion (now called PSR J0737−3039B, hereafter "B") to the millisecond pulsar (now called PSR J0737−3039A, hereafter "A") had not been found earlier, became clear when it was realized that B was only bright for two short parts of the orbit. For the remainder of the orbit, the pulsar B is extremely weak and only detectable with the most sensitive equipment. The detection of a young companion B around an old millisecond pulsar A confirms the evolution scenario proposed for recycled pulsars (e.g. [6,7]) and provides a truly unique testbed for relativistic gravity.

3 Strong-field tests of general relativity

Since neutron stars are very compact massive objects, the double pulsar (and other double neutron star systems) can be considered as almost ideal point sources for testing theories of gravity in the strong-gravitational-field limit. Tests can be performed when a number of relativistic corrections to the Keplerian description of an orbit, the so-called "post-Keplerian" (PK) parameters, can be measured. The experimental determination of the PK parameters is independent of the assumed theory of gravity [8,9], so that their measurement can be used to test general relativity and other theories [10].

Each theory of gravity predicts a certain value for the measured PK parameter that, for point masses with negligible spin contributions, depends only on the a priori unknown neutron star masses and the also precisely measurable Keplerian (K) parameters. With the two masses, $M_{\rm A}$ and $M_{\rm B}$, as the only two unknowns, the measurement of three or more PK parameters over-constrains the system. In other words, for a theory that describes a binary system correctly, the PK parameters produce theory-dependent lines in a $M_{\rm A} - M_{\rm B}$ diagram that all intersect in a single point. These lines are given by $M_{\rm B} = f(M_{\rm A}, \mathrm{K}, \mathrm{PK})$ where for GR f is given by solving the following expressions for the given PK parameters (listed to lowest post-Newtonian order) [9]:

$$\dot{\omega} = 3T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{1}{1-e^2}\ (M_A + M_B)^{2/3}, \tag{1}$$

$$\gamma = T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{M_B(M_A+2M_B)}{(M_A+M_B)^{4/3}}, \tag{2}$$

$$\dot{P}_b = -\frac{192\pi}{5} T_\odot^{5/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)}{(1-e^2)^{7/2}}\ \frac{M_A M_B}{(M_A+M_B)^{1/3}}, \tag{3}$$

$$r = T_\odot M_B, \tag{4}$$

$$s = T_\odot^{-1/3} \left(\frac{P_b}{2\pi}\right)^{-2/3} x \, \frac{(M_A+M_B)^{2/3}}{M_B}, \tag{5}$$

where P_b is the period and e the eccentricity and x the projected semi-major axis (measured in light-s) of the binary orbit. The masses M_A and M_B of A and B, respectively, are expressed in solar masses ($M_\odot$). We define the constant $T_\odot = GM_\odot/c^3 = 4.925490947\mu$s where G denotes the Newtonian constant of gravity and c the speed of light.

The first PK parameter, $\dot{\omega}$, is the easiest to measure and describes a relativistic advance of periastron. In the framework of GR, according to Eqn. 1, it provides an immediate measurement of the total mass of the system, $(M_A + M_B)$. The parameter γ denotes the average amplitude of delays in arrival times caused by variations in the gravitational redshift and time dilation (second order Doppler) as the pulsar moves in its elliptical orbit at varying distances from the companion and with varying speeds. The decay of the orbit due to gravitational wave damping is expressed by the change in orbital period, $\dot{P}_b$. The other two parameters, r and s, are related to the Shapiro delay caused by the gravitational field of the companion. In GR, the measured value of s can be identified with $\sin i$ where i is the inclination angle of the orbit.

Due to its faster spin period and its brightness throughout the entire orbit (apart from a $\sim$ 27-s eclipse at superior conjunction, see [3, 11, 12]), we can time A much more accurately than B, and all above PK parameters have been measured precisely for A's orbit ([3], Kramer et al. in prep.). In addition to tests enabled by these PK parameters, the access to the orbit of both neutron stars – by timing A *and* B – provides yet another constraint on gravitational theories that is qualitatively different from what has been possible with previously known double neutron stars: using Kepler's third law, the measurement of the projected semi-major axes of both orbits yields the mass ratio,

$$R(M_A, M_B) \equiv M_A/M_B = x_B/x_A. \tag{6}$$

For every realistic theory of gravity, we can expect R to follow this simple relation [10], at least to 1PN order. Most importantly, the R value is not only theory-independent, but also independent of strong-field (self-field) effects which is not the case for the PK parameters. In other words, any combination of masses derived from the PK parameters *must* be consistent with the mass ratio. With five PK parameters already available, this additional constraint makes the double pulsar the most overdetermined system to date where the most relativistic effects can be studied in the strong-field limit (Kramer et al. in prep.).

4 Timing of the double pulsar

The short eclipses in A's emission already indicate that we are observing the system almost completely edge-on. This is confirmed independently by measuring a Shapiro delay resulting in an orbital inclination angle i close to 90deg. Yet another method uses intensity variations due to the turbulent interstellar medium and also derives an inclination angle that is even closer to 90deg than obtained from timing observations (i.e. within (0.29 ± 0.14) deg) [13]. For that particular reason, it is crucial to verify all methods and the derived uncertainties on the orbital inclination angle. This includes the timing procedure and the implementation of the traditional DD timing model [8, 9].

4.1 Effects of geodetic precession

Firstly, we consider the measurement of the times-of-arrival (TOAs) which are obtained with a standard "template matching" procedure that involves a cross-correlation of the observed pulse profile with high signal-to-noise ratio template (e.g. [14]). Any change in the pulse profile could lead to systematic variations in the measured TOAs. We performed detailed studies of the profiles of A and B to investigate any possible profile changes with time as such as expected from another effect predicted by GR.

In GR, the proper reference frame of a freely falling object suffers a precession with respect to a distant observer, called geodetic precession. In a binary pulsar system this geodetic precession leads to a relativistic

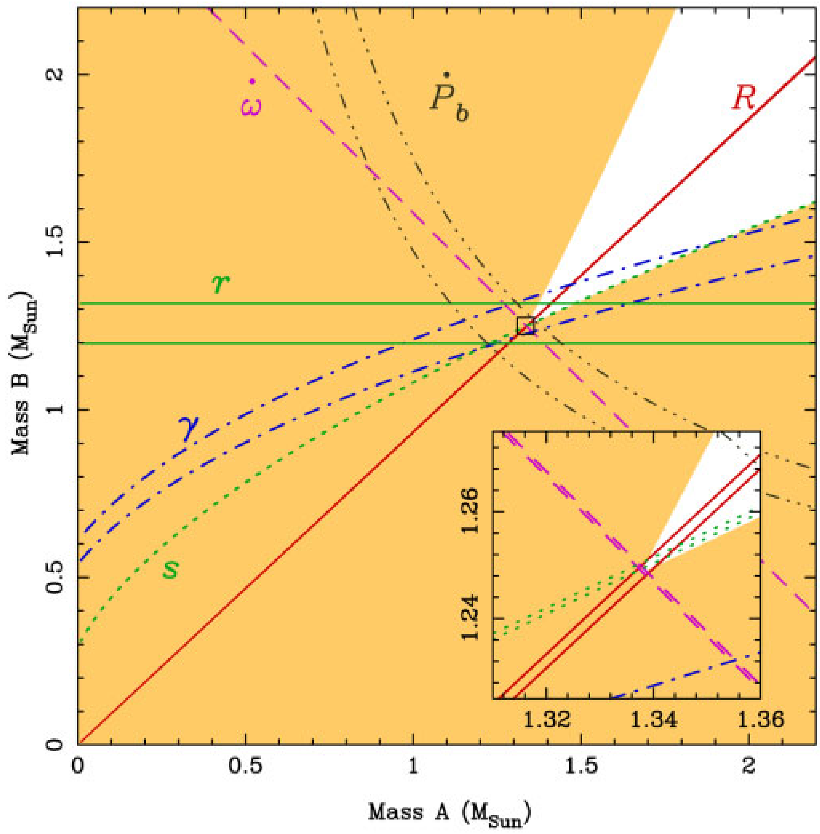

Fig. 1 'Mass–mass' diagram showing the observational constraints on the masses of the neutron stars in the double pulsar system J0737–3039. The shaded regions are those that are excluded by the Keplerian mass functions of the two pulsars. Further constraints are shown as pairs of lines enclosing permitted regions as given by the observed mass ratio and PK parameters as predicted by general relativity. Inset is an enlarged view of the small square encompassing the intersection of these constraints (see text).

spin-orbit coupling, analogous to spin-orbit coupling in atomic physics [15]. As a consequence, both pulsar spins precess about the total angular momentum, changing the relative orientation of the pulsars to one another and toward Earth. Since the orbital angular momentum is much larger than the pulsars' angular momenta, the total angular momentum is effectively represented by the orbital angular momentum. The precession rate [16] depends on the period and the eccentricity of the orbit as well as the masses of A and B. With the orbital parameters of the double pulsar, GR predicts precession periods of only 75 yr for A and 71 yr for B.

Geodetic precession has a direct effect on the timing as it causes the polar angles of the spins and hence the effects of aberration to change with time [10]. These changes modify the *observed* orbital parameters, like projected semi-major axis and eccentricity, which differ from the *intrinsic* values by an aberration dependent term, potentially allowing us to infer the system geometry [17]. Extracting the signature of these effects in the timing data is a goal for the years to come. Other consequences of geodetic precession can be expected to be detected much sooner and are directly relevant for the timing of A and B. These arise from variations in the pulse shape due to changing cuts through the emission beam as the pulsar spin axes precess. Moreover, geodetic precession also leads to a change in the relative alignment of the pulsar magnetospheres, so that the visibility pattern and even the profile of B should vary due to these changes as well.

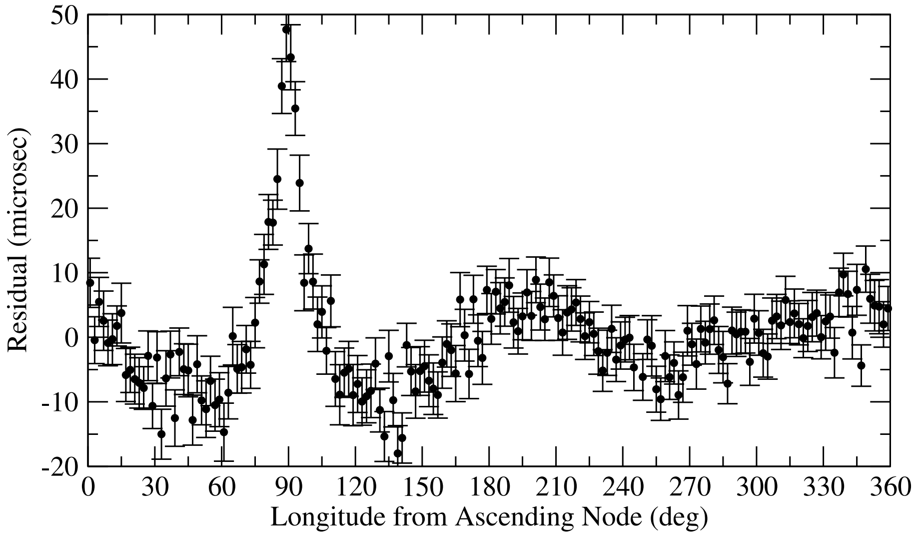

Fig. 2 The effect of the Shapiro delay caused by the gravitational potential of B seen in the timing residuals of A. The timing residuals obtained by fitting all model parameters except the Shapiro delay parameters r and s. The left-over structure represents the higher harmonics of the Shapiro delay that are unabsorbed by fits to the Keplerian parameters.

Indeed, studies of the profile evolution of B [18] reveal a clear evolution of B's emission on orbital and secular time-scales. The profile of B is changing with time, while also the light-curves of B (i.e. the visibility of B versus orbital phase) undergo clear changes. These phenomena may be caused by a changing magnetospheric interaction due to geometry variations resulting from geodetic precession. In any case, these changes require sophisticated timing analysis techniques, and work in progress is aiming to improve our ability to measure B's orbit and hence the mass ratio.

The study of the profile evolution of A [19] did not lead to the detection of any profile change over a period of 15 months. This present non-detection greatly simplifies the timing of A but does not exclude the possibility that changes may happen in the future. While the effects of geodetic precession could be small due to a near alignment of pulsar A's spin and the orbital momentum vector, the results could also be explained by observing the system at a particular precession phase. While this case appears to be relatively unlikely, it must not be excluded as such a situation had indeed occurred for PSR B1913+16 [20]. Indeed, a modelling of the results suggests that this present non-detection of profile changes is consistent with a rather wide range of possible system geometries. One conclusion that can be drawn, however, is that the observations are inconsistent with the large profile changes that had been predicted by some models [21].

4.2 A modification of the DD timing model

Scintillation measurements have recently suggested an orbital inclination angle [13] that appears to be inconsistent with results from the timing observations and the measurement of the Shapiro delay parameter s and its identification in GR as $s = \sin i$. The timing observations suggest an inclination angle that is close to but significantly different from $90\,\mathrm{deg}$. Comparing the two methods, one notes that the scintillation results are based on correlating the scintillation properties of A and B over the short time-span of the orbital motion when they are in conjunction to the observer. In contrast, the measurement of the inclination angle from timing measurements results from detecting significant harmonic structure in the post-fit residuals after parts of the Shapiro delay are absorbed in the fit for the Römer delay, i.e. the light travel time across the orbit. As shown in Figure 2, these structures are present throughout the whole orbit, so that the results

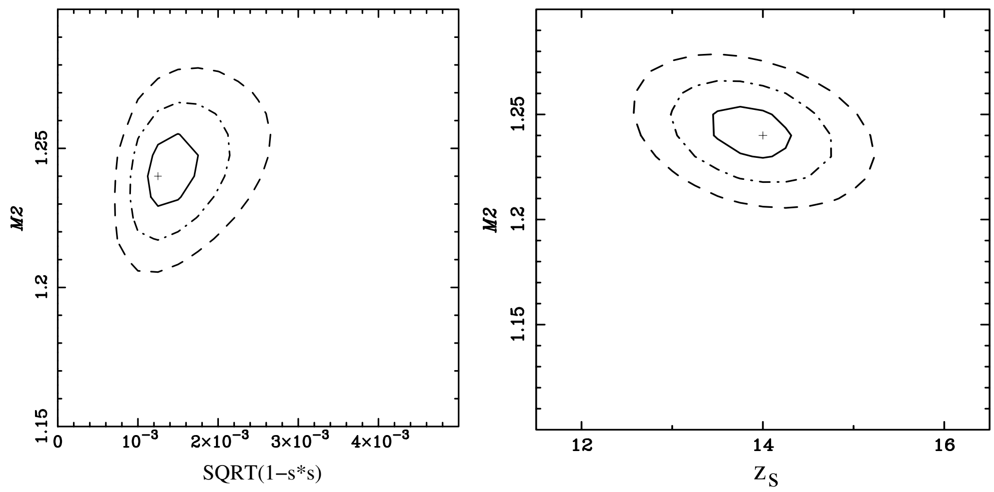

Fig. 3 Results of fitting the DD and DDS model to simulated data. The left plot shows the asymmetric χ^2 contours often obtained in fits of DD model. The right plots shows the application of the DDS model to the same artificial data. TEMPO determines the correct value for both z_s and its uncertainties, facilitated by the symmetric and regular χ^2 contours shown here.

from timing measurements may be expected to be more reliable. However, as all TOAs are associated with uncertainties, we need to make sure that a multi-parameter least-square fit of the DD model will reproduce the correct value of the PK parameters s and r despite possible numerical effects.

In order to study such possible effects and the performance of the standard timing software TEMPO[1] and its implementation of the DD timing model, we have made detailed simulations. Producing fake TOAs for a J0737−3039-like system, we varied the input parameter as $0.9 \leq s \leq 1.0$ and the assumed timing precision. For small TOA uncertainties, we can always recover the original s value by fitting the DD-model using TEMPO. However, comparing the standard TEMPO error estimates for s and r with estimates obtained from studying a corresponding χ^2 plane, the symmetric error bars given by TEMPO do not always correspond to the true uncertainties reflected by non-symmetric χ^2-contours if the TOA uncertainty is too large. This potential problem due to the non-linearity of the fitted parameters and correlations of the Shapiro delay parameters with the Römer delay in the orbit is well known. Hence, one usually explores an χ^2-plane evenly sampled in $\sqrt{1-s^2}$ and r to obtain reliable values and error estimates (see e.g. [22]). Increasing the TOA uncertainties, numerical fits to the fake TOAs assuming a $\sin i$ very close to unity (e.g. $\sin i = 0.99999$ or $i = 89.2$) sometimes results in fits with $s > 1$ due to numerical uncertainties. In order to remedy this situation we developed a modification of the DD timing model following a suggestion by Thibault Damour (priv. communication).

In the DD model, we fit for r and s which in GR becomes $s = \sin i$ where r is identical with the companion mass apart from a constant factor, $T_\odot$ (see Eqn. 4). In the new model, called DDS (for DD-Shapiro), we write

$$s = 1 - e^{-z_s} \tag{7}$$

where z_s replaces s as our new fit parameter. It follows that

$$z_s = -\ln(1 - s). \tag{8}$$

[1] http://pulsar.princeton.edu/tempo/

The advantage becomes apparent when we compare this expression to the Shapiro delay term, Δ_s in the timing formula, in particular when comparing it to low-eccentricity pulsars for which (e.g. [23])

$$\Delta_s = -2r \ln(1 - s \sin \Phi) \tag{9}$$

where Φ is the orbital phase measured from the ascending node. At $\Phi = \pi/2$, the maximum delay is obtained

$$\Delta_s^{\max} = -2r \ln(1 - s) \tag{10}$$

which has obvious similarities to our definition of z_s,

$$\Delta_s^{\max} = 2\ r\ z_s \tag{11}$$

or

$$z_s = \Delta_s^{\max}/2r. \tag{12}$$

Due to the nature of this simple transformation, a fit of the TOAs to the DD and DDS models always produces the same results. In addition, however, at large inclination angles the uncertainties on z_s derived by TEMPO are still consistent with those obtained from studies of corresponding χ^2 hyperspheres, removing the need for the often computationally expensive calculation of the χ^2 plane (see Figure 3). Using the DDS model, it is in particular impossible that numerical uncertainties lead to fit results which in GR correspond to values $\sin i > 1.0$. We are aware that the DDS model therefore represents a restriction of the parameter space which may be allowed by alternative theories of gravity.

The application of the DD and DDS model to the real TOAs produces consistent results and verifies the previous findings that s is significantly lower than unity and still appears to be inconsistent with the scintillation results. We have studied other effects possible affecting the timing results such as a possible variation of the dispersion measure as a function of orbital phase. However, the non-detection of any such effect (see Fig. 4) leads us to the conclusion that in contrast unmodelled effects may have altered the scintillation results and the derived uncertainties on the inclination angle. An exciting explanation for the discrepancy may be that the emission of A suffers measurable refraction while propagating through the magnetosphere of B. If that were indeed the case, we would have a direct handle onto the magneto-ionic properties of B's magnetosphere for the first time, e.g. corresponding plasma densities in B's magnetosphere would need to be relatively large.

5 Present results

The present timing results already indicate that the proper motion of this system is surprisingly small. While a significant measurement of a proper motion vector via pulsar timing will be available shortly (Kramer et al. in prep), the present limit suggests a systemic velocity of less than 30 km/s for a dispersion measure distance of 600 pc [24].[2] While such a small velocity may be indicative of a small kick imparted onto B during its supernova explosion [25], other studies find this limit still to be consistent with a kick of average magnitude [26]. In any case, such a small velocity is good news for tests of GR. Usually, the observed value of $\dot{P}_b$ is positively biased by an effect known as secular acceleration arising from a relative motion and acceleration of the system (e.g. [27]). Computing the magnitude of this observational bias using the obtained limit on the proper motion, however, suggests that the contribution is much less than 1%, so that the orbital decay measurement will be available for another precise GR test.

[2] We note that this small velocity is marginally consistent with the 66 km/s derived from scintillation measurements as the latter value is not corrected for the relative motion of the Earth [13].

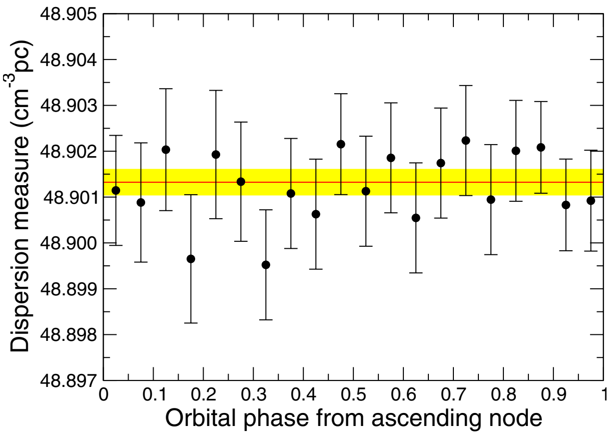

Fig. 4 Dispersion measure determined independently for different phases of the binary orbit. No significant variation is detected.

We can take the most precise parameters (i.e. the mass ratio R, the advance of periastron $\dot{\omega}$ and the Shapiro delay parameter s) to test theories of gravity. Assuming that GR is the correct theory of gravitation, we use Eqn. 1 to derive the total mass of the system and combine it with the observed mass ratio to obtain $M_A = 1.338 \pm 0.001 M_\odot$ and $M_B = 1.249 \pm 0.001 M_\odot$. Using these precisely determined masses we compute the Shapiro delay parameter s as predicted by GR and compare it to the observed value. We find that GR passes this test at the 0.1% level (Kramer et al. in prep.). This is the most stringent test of GR in the strong-field limit so far.

6 Future

In the near and far future, the precision of the determined parameters will increase further, because of the available longer time span and also the employment of better instrumentation. In a few years, we should be able to measure additional PK parameters, including those which arise from a relativistic deformation of the pulsar orbit and those which find their origin in aberration effects and their interplay with geodetic precession (see [10]). On secular time scales we will even achieve a precision that will require us to consider post-Newtonian (PN) terms that go beyond the currently used description of the PK parameters. Indeed, the equations for the PK parameters given earlier are only correct to lowest PN order. However, higher-order corrections are expected to become important if timing precision is sufficiently high. While this has not been the case in the past, the double pulsar system may allow measurements of these effects in the future [3].

One such effect involves the GR prediction that, in contrast to Newtonian physics, the neutron stars' spins affect their orbital motion via spin-orbit coupling. This effect would be visible most clearly as a contribution to the observed $\dot{\omega}$ in a secular [16] and periodic fashion [28]. For the J0737$-$3039 system, the expected contribution is about an order of magnitude larger than for PSR B1913+16, i.e. 2×10^{-4} deg yr^{-1} (for A, assuming a geometry as determined for PSR B1913+16 [20]). As the exact value depends on the pulsars' moment of inertia, a potential measurement of this effect allows the moment of inertia of a neutron star to be determined for the first time [29]. To be successful requires the measurement of at least two other parameters to a similar accuracy as $\dot{\omega}$. While this is a tough challenge, e.g. due to the expected profile variations caused by geodetic precession, the rewards of such a measurement and its impact on the study of the equation of state of neutron stars make it worth trying.

7 Summary and conclusions

With the measurement of five PK parameters and the unique information about the mass ratio, the PSR J0737$-$3039 system provides a truly unique test-bed for relativistic theories of gravity. So far, GR also passes this test with flying colours. The precision of this test and the nature of the resulting constraints go beyond what has been possible with other systems in the past. The test achieved so far is, however, only the beginning of a study of relativistic phenomena that can be investigated in great detail in this wonderful cosmic laboratory.

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