Gravitational-radiation losses from the pulsar–white-dwarf binary PSR J1141–6545

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Pulsars in close binary orbit around another neutron star or a massive white dwarf make ideal laboratories for testing the predictions of gravitational radiation and self-gravitational effects. We report new timing measurements of the pulsar–white-dwarf binary PSR J1141–6545, providing strong evidence that such asymmetric systems have gravitational wave losses that are consistent with general relativity. The orbit is found to be decaying at a rate of $1.04 \pm 0.06$ times the general relativistic prediction and the Shapiro delay is consistent with the orbital inclination angle derived from scintillation measurements. The system provides a unique test-bed for tensor-scalar theories of gravity; our current measurements place stringent constraints in the theory space, with a limit of $\alpha_0^2 < 2.1 \times 10^{-5}$ for weakly non-linear coupling and an asymptotic limit of $\alpha_0^2 < 3.4 \times 10^{-6}$ for strongly non-linear coupling, where $\alpha_0$ is the linear coupling strength of matter to an underlying scalar field. This asymptotic limit is nearly three times smaller than the Cassini bound ($\alpha_0^2 \approx 10^{-5}$).

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Introduction.—Einstein’s general theory of relativity (GR) has passed all experimental tests so far with complete success, which makes it one of the most celebrated theories in modern physics [1]. While the most precise tests have been conducted in the weak-field conditions of the solar system [2, 3], massive and compact astronomical objects such as neutron stars and black holes, in particular pulsars in close binary orbits with another neutron star or a massive white dwarf (i.e. relativistic binary pulsars), allow testing GR in strong-field conditions [4, 5, 6]. These tests have confirmed GR at an impressive level of better than 1% [2, 3, 4, 5, 6].

While GR is indeed the most successful theory of gravity, it may conceivably break down under extreme strong-field conditions where other theories of gravity may apply. Tensor-scalar theories, which invoke a coupling between matter and an underlying scalar field (in addition to the standard space-time tensor field), are thought to be the most natural alternatives to GR [7, 8]. The most well-known in this framework is the Jordan-Brans-Dicke theory, with a linear coupling between matter and scalar field: $a(\psi) = \alpha_0 \psi$, whilst a more general description involves a two-dimensional parameter space: $a(\psi) = \alpha_0 \psi + \frac{1}{2} \beta_0 \psi^2$, where $\psi$ is the strength of the scalar field; $a(\psi)$ is the coupling strength between the scalar field and matter; $\alpha_0$ and $\beta_0$ are the coupling parameters. The scalar field does not exist in GR and therefore $(\alpha_0, \beta_0) = (0, 0)$. Possible deviations from GR are thus constrained by experimentally imposed bounds on $\alpha_0$ and $\beta_0$. While several tests have been devised for this (see [8, 9, 10] for recent reviews), current best limits come from timing binary pulsars ($\beta_0 > -4.5$) and the Cassini time-delay experiment ($\alpha_0^2 < 10^{-5}$; [2]).

The binary-pulsar tests so far [4, 5, 6] have focused on systems that consist of two almost identical neutron stars (i.e. symmetric systems in which both the objects are of nearly equal mass and size). PSR J1141–6545, on the other hand, comprising a strongly self-gravitating neutron star and a (relatively) weakly self-gravitating white dwarf, is a gravitationally asymmetric system and thus provides a unique laboratory for testing GR and alternative theories of gravity [8]. The asymmetry here is due to the self-gravity ($\varepsilon$) or the compactness of the two bodies (given by $\varepsilon = -GM/(Rc^2)$, where $M$ and $R$ are mass and radius respectively). Since $\varepsilon \sim -0.2$ for a neutron star and $\sim -10^{-4}$ for a white dwarf, a neutron star-white dwarf binary is a very asymmetric system.

Discovered in 1999, PSR J1141–6545 is a relatively young pulsar (characteristic age $\sim 1.4$ Myr) spinning at a rate of once every 394 ms and is in a 4.74-hr orbit with a moderate eccentricity of $\sim 0.17$ [11]. Early studies suggested that the pulsar lies at a minimum distance of 3.7 kpc [12] and the orbit is inclined at an angle of $76^\circ \pm 2^\circ.5$ with respect to the plane of the sky [13]. The orbital period derivative from initial timing analysis was shown to be consistent with GR at the 25% level [14] and, more recently, observations over a 6-yr time span have unveiled remarkable changes in both the pulse shape and polarisation, which are attributed to geodetic precession resulting from general relativistic spin-orbit coupling [15].

In this article, we report measurements of four post-Keplerian parameters for PSR J1141–6545: advance of periastron $\omega$, time dilation and gravitational redshift $\gamma$, the Shapiro delay parameter $s$, and the orbital period derivative $\dot{P}_b$, that allow us to determine the masses of the pulsar and its companion; demonstrate that gravitational wave radiation losses are consistent with those predicted by GR; and place stringent limits on tensor-scalar theories of gravity.

Timing Observations and Analysis.—Timing observations of PSR J1141–6545 were undertaken using the 64-m Parkes radio telescope in New South Wales, Australia, between 2001 January and 2007 May. Data were recorded primarily in the 20 cm radio band, while limited data were gathered in the 50 cm band. Early observations (2001 to 2002) made use of a multichannel filterbank as the backend, recording data over a bandwidth of 256 MHz, while data from 2003 onward were recorded us-
TABLE I: Timing parameters of PSR J1141−6545.

| Parameter | Value |
|-----------|-------|
| Spin and astrometric parameters: |       |
| Right ascension, α (J2000) | 11°41′07″.0140(2) |
| Declination, δ (J2000) | −65°45′19″.1131(15) |
| Pulse frequency, ν (s\(^{-1}\)) | 2.538729369926(1) |
| Reference epoch (MJD) | 51369.852500 |
| Dispersion measure (pc cm\(^{-3}\)) | 116.080(1) |
| First derivative of pulse frequency (s\(^{-2}\)) | −2.767986(1) × 10\(^{-14}\) |

Keplerian parameters:

- Orbital period, \(P_0\) (days) | 0.1976509593(1) |
- Projected semi-major axis, \(a\) (s) | 1.858922(6) |
- Orbital eccentricity, \(e\) | 0.171884(2) |
- Time of periastron passage, \(T_0\) (MJD) | 51369.8545515(9) |
- Longitude of periastron, \(\omega\) (°) | 42.4561(16) |

Post-Keplerian parameters:

- Advance of periastron, \(\omega\) (° yr\(^{-1}\)) | 5.3096(4) |
- Gravitational redshift parameter, \(\gamma\) (ms) | 0.000773(11) |
- Orbital period derivative, \(\dot{P}_0\) | −0.403(25) × 10\(^{-12}\) |

Figures in parentheses represent the nominal 1-sigma uncertainties in the least-significant digits quoted.

The pulse arrival times were computed by correlating the observed pulse profiles with template profiles of high signal-to-noise ratio constructed from long integrations of data. A total of 12,842 pulse times-of-arrival (TOAs) were measured. The remarkable changes observed in the pulse profile over our seven-year long observing span, while exciting for studies of geodetic precession and modeling the pulsar emission geometry, have complicated our timing analysis. In order to minimize the systematics caused by secular profile changes, we adopted a strategy which involves the use of a standard (template) profile that is a function of time. The final TOAs were analyzed using the standard timing package TEMPO, fitting for the pulsar spin, astrometric and Keplerian parameters, as well as three post-Keplerian parameters according to the relativistic and theory-independent timing model of Damour and Deruelle (DD) \(^{16}\). The final root mean square post-fit residual is 154 μs. The measured pulsar and binary system parameters are listed in Table 1.

Tests of General Relativity.—In double neutron star systems and in close eccentric systems such as PSR J1141−6545, the gravitational fields are so strong that the application of relativistic gravity becomes essential in timing models. For such systems, the observed pulse arrival times are modified by relativistic effects, which are potentially measurable through long-term (several year) timing observations. These relativistic effects may manifest themselves in various ways; for instance a temporal change in the period or orientation of the orbit, or an additional time delay (the Shapiro delay) resulting from the curvature of space-time when pulses pass near the massive companion. These effects can be modeled in terms of the post-Keplerian (PK) parameters, which are essentially some phenomenological corrections and additions to the Keplerian orbital parameters \(^{16}\). These PK parameters have different dependencies in different theories of gravity, and thus facilitate important tests of theories of gravity \(^{1,17}\). In any theory of gravity, the PK parameters can be expressed as functions of the pulsar and companion masses and the easily measurable Keplerian parameters. A binary pulsar requires two PK parameters to completely determine the inclination and masses of the system. Measurement of three or more PK parameters over-determines the system, and thus can provide one (or more) test(s) of gravitational theories through self-consistency checks.

The orbital period derivative \(\dot{P}_b\) is a crucial parameter as it is still the only observable that has ever verified the existence of gravitational waves. Relative to previous timing analysis \(^{14}\), the measurement precisions on the PK parameters have now improved by up to a factor of 4 and, most notably, \(\dot{P}_b\) is determined to be \((-4.03 ± 0.25) \times 10^{-13}\). This measured value \((\dot{P}_b^{\text{meas}})\) is a combination of the orbital decay due to the emission of gravitational radiation \((\dot{P}_b^{\text{GR}})\) and contributions resulting from both real and apparent accelerations of the binary system along the line of sight; i.e.,

\[
\dot{P}_b^{\text{meas}} = \dot{P}_b^{\text{GR}} + \dot{P}_b^{\text{kin}} + \dot{P}_b^{\text{Gal}}
\]

where “Gal” and “kin” refer to the Galactic and kinematic contributions respectively \(^{18}\). The kinematic contribution, known as the Shklovskii effect (an apparent acceleration of the system due to its space motion, \(v_t\)), is given by \(v_t^2/(c d)\), where \(d\) is the pulsar distance and \(c\) is the speed of light. The Galactic contributions include differential rotation in the plane of the Galaxy and acceleration in the Galactic gravitational potential. Given a transverse speed of \(115 ± 15\) km s\(^{-1}\) deduced from scintillation observations and a pulsar distance of 3.7 kpc, we estimate \(\dot{P}_b^{\text{kin}} = (6.71 ± 1.73) \times 10^{-15}\) and \(\dot{P}_b^{\text{Gal}} = (−5.05 ± 0.44) \times 10^{-15}\). Subtracting these from the measured \(\dot{P}_b\), we obtain an intrinsic value \((-4.01 ± 0.25) \times 10^{-13}\) for \(\dot{P}_b^{\text{GR}}\). This is \(1.04 ± 0.06\) times the general relativistic prediction and corresponds to a shrinkage of the pulsar’s orbit at a rate of approximately 2 mm per day.

As the measurement of any two PK parameters allows solving for the two unknown stellar masses, our measurement of three PK parameters offers an independent test of GR. These results can be displayed elegantly in
a “mass-mass” diagram as shown in Figure 1. Measurement of the PK parameters gives curves on this diagram that are, in general, different for different theories of gravity but should intersect at a single point (i.e. at a pair of mass values) if the theory is valid. Our results confirm that GR is a correct theory of gravity for asymmetric binary systems, thereby extending the range of systems for which GR provides an accurate description.

Given this, it is justifiable to apply the Damour Deruelle GR (DDGR) formalism (as implemented in TEMPO) to determine the pulsar and companion masses [16, 17]. This timing model is in the framework of DD but assumes GR to be the true theory of gravity. It uses measurements of the PK parameters $\omega$ and $\gamma$ to solve for the companion and total masses of the system ($m_c$ and $m_{\text{tot}}$ respectively) and to model the Shapiro delay. The pulsar mass ($m_p$) is then given by $m_{\text{tot}} - m_c$. The best-fit values from such a DDGR fit to our timing data are $m_{\text{tot}} = 2.2892 \pm 0.0003$ $M_\odot$ and $m_c = 1.02 \pm 0.01$ $M_\odot$, which implies the pulsar mass $m_p = 1.27 \pm 0.01$ $M_\odot$. These mass estimates imply an orbital inclination angle ($i$) of $73^\circ \pm 1^\circ.5$. This is in excellent agreement with independent constraints of over a range of mass values from 0.2 to 1 (i.e. $i$ from $10^\circ$ to $90^\circ$) and the companion mass at the value determined by $m_{\text{tot}} = 2.2892$ $M_\odot$ and the mass function $(f_p) = 0.176701$ $M_\odot$. $i = 76^\circ \pm 2^\circ.5$ derived from the orbital modulation of the pulsar’s scintillation velocity [13].

Figure 2 shows a goodness-of-fit plot for $i$ values between 0.2 and 1, in which the companion mass was set to a value determined by the precisely known systemic mass $m_{\text{tot}}$ and the pulsar mass function, $f_p = (m_c \sin i)^{3/2}/m_{\text{tot}}^2 = 0.176701$ $M_\odot$. Such an approach is justifiable as the relativistic $\omega$ is determined at a very high precision and hence traces out a unique locus in the mass-mass diagram, with each point on the locus implying a unique inclination angle. While the use of the DDGR-derived $m_{\text{tot}}$ means assumption of GR, the timing model used is DD. The two-sigma range in the inclination angle (72$^\circ$.6 to 79$^\circ$.4) indicated by this curve is consistent with completely independent constraints derived from the scintillation measurements and thus, effectively, provides yet another confirmation of GR in this system.

The revised mass estimate of PSR J1141−6545 makes it one of the lighter neutron stars currently known. Although the pulsar’s progenitor was initially the lighter star in the original binary pair, mass transfer from the white dwarf’s progenitor made it large enough to explode as a supernova even though its companion was not large enough to do so [19]. Being the second star to evolve in the binary, PSR J1141−6545 is somewhat similar to pulsar B in the double pulsar system and the companion to PSR J1756−2251 [6, 20]. It seems probable therefore, that the progenitors to these pulsars were of lower mass and that the mass of a neutron star is related to that of the progenitor. Recycled pulsars, or those with higher eccentricities, appear to be heavier [20, 21] either due to mass accretion [22] or higher initial masses.

**Alternative Theories of Gravity.**—Deviations from GR inherent to most alternative theories of gravity are best detectable in strong gravitational fields, and hence binary-pulsar measurements are indispensable in testing such theories [23]. In particular, the gravitationally asymmetric nature of the PSR J1141−6545 system makes it a unique testing ground for tensor-scalar theo-

![Figure 1: Graphical summary of relativistic parameters from timing measurements of the PSR J1141−6545 binary system. The shaded area is excluded from a consideration of Kepler’s laws and the other constraints are based on the measured PK parameters (shown as pairs of lines, with the line separation indicating the measurement uncertainty) interpreted within the framework of GR.](image1)

![Figure 2: Current constraints on the orbital inclination angle (i) of the PSR J1141−6545 system. The smooth curve represents values of $\Delta \chi^2$ obtained when $i$ was held fixed at a range of values from 0.2 to 1 (i.e. $i$ from 10$^\circ$ to 90$^\circ$) and the companion mass at the value determined by $m_{\text{tot}} = 2.2892$ $M_\odot$ and the mass function $(f_p) = 0.176701$ $M_\odot$.](image2)
strong confirmation of GR in gravitationally asymmetric binary systems. The measured orbital decay is in agreement with the GR prediction and the Shapiro delay is consistent with independent measurements of the orbital inclination angle. The pulsar and companion masses are determined to be $m_\text{p} = 1.27 \pm 0.01 \, M_\odot$ and $m_\text{s} = 1.02 \pm 0.01 \, M_\odot$ respectively. Stringent limits are placed on tensor-scalar theories of gravity, with an asymptotic limit of $\alpha_0^2 < 3.4 \times 10^{-6}$, cutting well below the Cassini limit for large values of the coupling parameter $\beta_0$ and hence providing the lowest limit in that range. For small values of $\beta_0$, the limit is $\alpha_0^2 < 2.1 \times 10^{-5}$ and thus weaker than that derived from the Cassini experiment.

Continued timing of this pulsar looks very promising. Currently $P_b$ is determined at a 6% precision, the uncertainty in which is expected to decrease as $T^{-5/2}$, where $T$ is the observing time span. We thus anticipate approaching a precision near 2% by 2012. At such high precision, contributions from the kinematic and Galactic contributions will start dominating the error budget. While the Galactic term $P_b^{\text{Gal}}$ is hard to determine accurately, the kinematic Shklovskii contribution $P_b^{\text{kin}}$ can be assessed better when an independent measurement becomes available for the pulsar’s transverse motion. Fortunately, the pulsar’s location is such that $P_b^{\text{kin}}$, and thus may cancel out a large fraction of it if the pulsar is moving at $\sim 100 \, \text{km/s}$ or faster, potentially resulting in a net contamination that is well below 1%. This will enable even more precise tests in the future and will place the most stringent constraints on alternative theories of gravity.

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