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

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Pulsars in close binary systems with white dwarfs or other neutron stars 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. The orbit is found to be decaying at a rate of 1.04 ± 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 testbed for tensor-scalar theories of gravity. Our measurements place stringent constraints in the theory space, with a limit of $\alpha_0^2 < 2.1 \times 10^{-5}$ for weakly nonlinear coupling and an asymptotic limit of $\alpha_0^2 < 3.4 \times 10^{-6}$ for strongly nonlinear coupling (where α_0 is the linear coupling strength of matter to an underlying scalar field), which is nearly 3 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 other neutron stars or massive white dwarfs (i.e. relativistic binary pulsars), allow testing GR in strong-field conditions [4–6]. These tests have confirmed GR at an impressive level of better than 1% [2–6].

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: $a(\psi) = \alpha_0\psi$, while a more general description involves a two-dimensional parameter space: $a(\psi) = \alpha_0\psi + \frac{1}{2}\beta_0\psi^2$, where ψ is the strength of the scalar field; $a(\psi)$ is the coupling strength between the scalar field and matter; α_0 and β_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 α_0 and β_0. While several tests have been devised for this (see [8–10] 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 [4–6] 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 (ε) or the compactness of the two bodies [given by $\varepsilon = -GM/(Rc^2)$, where M and R are mass and radius, G is the gravitational constant, and c is the speed of light, 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 ~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 ~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 $76° \pm 2.5°$ 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 polarization, 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 $\dot{\omega}$, time dilation and gravitational redshift γ, 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 using the Caltech-Parkes-Swinburne baseband recorder 2, which coherently dedisperses data over two adjacent 64-MHz bands, thus yielding a net bandwidth of 128 MHz. The data were folded at the predicted topocentric period of the pulsar, where the adopted integration time varied from 60 seconds (2001 to 2003) to 300 seconds (2004 onward), to account for almost a factor of 2 decrease observed in the pulsar's mean flux density over this period. The measurement uncertainties in the pulse arrival times have significantly degraded over this period, as a result of a dramatic increase observed in the pulse width (nearly by a factor of 2 over seven years) probably caused by precession of the pulsar spin axis.

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 I.

TABLE I. Timing parameters[a] of PSR J1141–6545.

Spin and astrometric parameters:	
Right ascension, α (J2000)	$11^h41^m07^s.0140(2)$
Declination, δ (J2000)	$-65°45'19''.1131(15)$
Pulse frequency, ν (s^{-1})	2.538 729 369 926(1)
Reference epoch (MJD[b])	51 369.852 500
Dispersion measure ($\mathrm{pc\,cm}^{-3}$)	116.080(1)
First derivative of pulse frequency (s^{-2})	$-2.767\,986(1) \times 10^{-14}$
Keplerian parameters:	
Orbital period, P_b (days)	0.197 650 959 3(1)
Projected semimajor axis, x (s)	1.858 922(6)
Orbital eccentricity, e	0.171 884(2)
Time of periastron passage, T_0 (MJD)	51 369.854 551 5(9)
Longitude of periastron, ω (°)	42.4561(16)
Post-Keplerian parameters:	
Advance of periastron, $\dot{\omega}$ ($°\,\mathrm{yr}^{-1}$)	5.3096(4)
Gravitational redshift and time dilation, γ (ms)	0.000 773(11)
Orbital period derivative, $\dot{P}_\mathrm{b}$	$-0.403(25) \times 10^{-12}$

[a]Figures in parentheses represent the nominal 1σ uncertainties in the least-significant digits quoted.
[b]MJD indicates Modified Julian Day.

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 overdetermines the system, and thus can provide one (or more) test (s) of gravitational theories through self-consistency checks.

The orbital period derivative $\dot{P}_\mathrm{b}$ 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, $\dot{P}_\mathrm{b}$ is determined to be $(-4.03 \pm 0.25) \times 10^{-13}$. This measured value ($\dot{P}_\mathrm{b}^\mathrm{meas}$) is a combination of the orbital decay due to the emission of gravitational radiation ($\dot{P}_\mathrm{b}^\mathrm{GR}$) and contributions resulting from both real and apparent accelerations of the binary system along the line of sight; i.e.,

$$\dot{P}_\mathrm{b}^\mathrm{meas} = \dot{P}_\mathrm{b}^\mathrm{GR} + \dot{P}_\mathrm{b}^\mathrm{kin} + \dot{P}_\mathrm{b}^\mathrm{Gal}, \tag{1}$$

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 $v_t^2/(cd)$, 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 $115 \pm 15\ \mathrm{km\,s^{-1}}$ deduced from scintillation observations and a pulsar distance of 3.7 kpc, we estimate $\dot{P}_\mathrm{b}^\mathrm{kin} = (6.71 \pm 1.73) \times 10^{-15}$ and $\dot{P}_\mathrm{b}^\mathrm{Gal} = (-5.05 \pm 0.44) \times 10^{-15}$. Subtracting these from the measured $\dot{P}_\mathrm{b}$, we obtain an intrinsic value $(-4.01 \pm 0.25) \times 10^{-13}$ for $\dot{P}_\mathrm{b}^\mathrm{GR}$. 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 Fig. 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 $\dot{\omega}$ and γ to solve for the companion and total masses of the system (m_c and m_tot, respectively) and to model the Shapiro delay. The pulsar mass (m_p) is then given by $m_\mathrm{tot} - m_\mathrm{c}$. The best-fit values from such a DDGR fit to our timing data are $m_\mathrm{tot} = 2.2892 \pm 0.0003\ \mathrm{M}_\odot$ and $m_\mathrm{c} = 1.02 \pm 0.01\ \mathrm{M}_\odot$, which implies the pulsar mass $m_\mathrm{p} = 1.27 \pm 0.01\ \mathrm{M}_\odot$. These mass estimates imply an orbital inclination angle (i) of $73° \pm 1.5°$. This is in excellent agreement with independent constraints of $i = 76° \pm 2.5°$ derived from the orbital modulation of the pulsar's scintillation velocity [13].

Figure 2 shows a goodness-of-fit plot for $\sin i$ values between 0.2 and 1, in which the companion mass was set to a value determined by the precisely known systemic mass m_tot and the pulsar mass function, $f_p = (m_\mathrm{c} \sin i)^3 / m_\mathrm{tot}^2 = 0.176\,701\ \mathrm{M}_\odot$. Such an approach is justifiable as the relativistic $\dot{\omega}$ 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 we make use of the DDGR-derived m_tot, the timing model used for the analysis is DD. The two-sigma range in the inclination angle (72.6° to 79.4°) 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

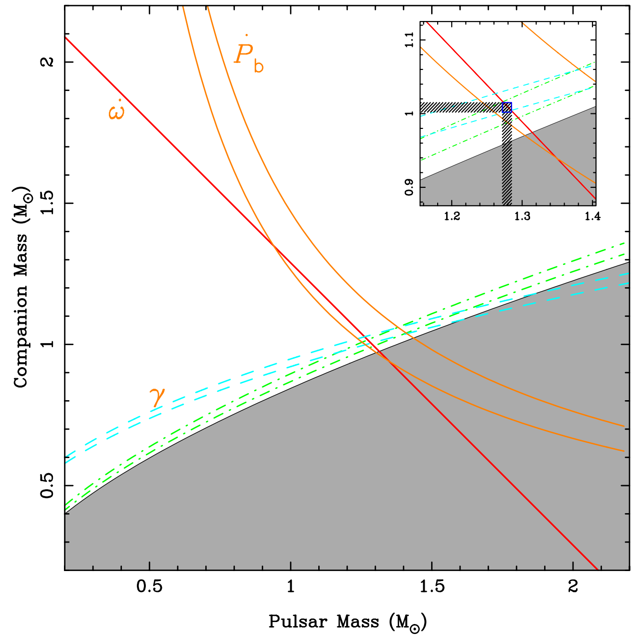

FIG. 1 (color online). Graphical summary of relativistic parameters from timing measurements of the PSR J1141–6545 binary system. The shaded area is excluded from a consideration of Kepler's laws and the other constraints are based on the measured PK parameters (shown as pairs of lines, with the line separation indicating the measurement uncertainty) interpreted within the framework of GR. The systemic mass $m_\mathrm{tot} = 2.2892 \pm 0.0003\ \mathrm{M}_\odot$ is very accurately defined from $\dot{\omega}$ and is shown by the straight solid lines; the γ term constrains the system to lie between the dashed lines, and $\dot{P}_\mathrm{b}$ between the pair of curved solid lines. The $\sin i$ measurement from scintillation analysis [13] is shown as the pair of dot-dashed lines. The hatched areas (inset) accentuate the masses allowed within the framework of GR.

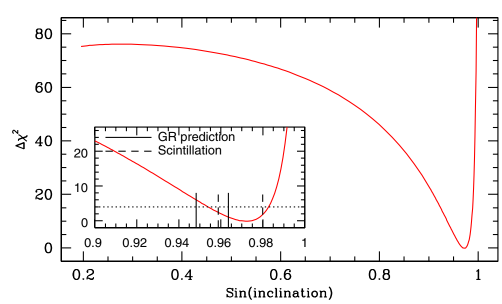

FIG. 2 (color online). Current constraints on the orbital inclination angle (i) of the PSR J1141–6545 system. The smooth curve represents values of $\Delta\chi^2$ obtained when $\sin i$ was held fixed at a range of values from 0.2 to 1 (i.e. i from 10° to 90°) and the companion mass at the value determined by $m_\mathrm{tot} = 2.2892\ \mathrm{M}_\odot$ and the mass function $(f_p) = 0.176\,701\ \mathrm{M}_\odot$.

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 theories [8], the best motivated alternatives to GR. This is because for such systems, tensor-scalar theories predict the emission of a large amount of dipolar scalar waves in the form of gravitational radiation loss (as opposed to predominantly quadrupolar radiation predicted by GR). This effect is strongly suppressed in double neutron star binaries, and as a result our timing measurements of PSR J1141–6545 impose much tighter constraints on these theories than those possible by PSRs B1913 + 16, B1534 + 12, and J0737–3039 [8,10]. In fact, the measurement of an orbital decay that is in accord with GR would naturally exclude a significant part of the theory space.

A parameter of particular interest is the linear coupling strength α_0, for which the asymptotic limit scales as the square root of the measurement uncertainty in $\dot{P}_b$ [8]. This limit corresponds to strongly nonlinear coupling (the quadrature coupling strength, $\beta_0 \sim 10$ or larger). A simple extrapolation based on our current measurements yields $\alpha_0^2 < 3.4 \times 10^{-6}$ in this regime. This is 3 times smaller than the Cassini bound ($\alpha_0^2 \leq 1.15 \times 10^{-5}$), and thus provides the current best limit in that part of the theory space. For smaller values of β_0 (i.e. weakly nonlinear coupling) however, the limit is weaker and is a function of β_0. In the special case of linear coupling (Brans-Dicke; $\beta_0 = 0$), it is reduced by a factor of $4\varepsilon_{ns}^2$, where ε_{ns} is the self-gravity of the neutron star [8]. Assuming $\varepsilon_{ns} = 0.2$, we derive $\alpha_0^2 < 2.1 \times 10^{-5}$ for this regime, which is nearly twice the Cassini limit (such values depend on the assumed equation of state and $\varepsilon_{ns} = 0.2$ may be overoptimistic). Thus, the limit imposed by our current data is weaker than that from Cassini for linear or weakly nonlinear coupling but becomes increasingly stringent for strongly nonlinear coupling and it should improve upon the Cassini bound somewhere within the range $5 \lesssim \beta_0 \lesssim 10$. As our timing precision improves over time, these limits are expected to become even more stringent, eventually cutting well below the Cassini bound at much lower values of β_0.

Conclusions and future prospects.—Our long timing campaign on PSR J1141–6545 has led to precise measurements of its PK parameters $\dot{\omega}$, γ, and $\dot{P}_b$, providing 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 $m_p = 1.27 \pm 0.01\ M_\odot$ and $m_c = 1.02 \pm 0.01\ M_\odot$, 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 β_0 and hence providing the lowest limit in that range. For small values of β_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 $\dot{P}_b$ 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, contaminations from the kinematic and Galactic contributions will start dominating the error budget [18]. While the Galactic term $\dot{P}_b^{Gal}$ is hard to determine accurately, the kinematic Shklovskii contribution $\dot{P}_b^{kin}$ can be assessed better when an independent measurement becomes available for the pulsar's transverse motion. Fortunately, the pulsar's location is such that $\dot{P}_b^{Gal}$ (dominated by differential rotation in the plane of the Galaxy) is of opposite sign to $\dot{P}_b^{kin}$, and thus may cancel out a large fraction of it if the pulsar is moving at $\sim 100\ \mathrm{km\,s^{-1}}$ 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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[1] C. M. Will, Living Rev. Relativity **9**, 3 (2006).
[2] B. Bertotti *et al.*, Nature (London) **425**, 374 (2003).
[3] J. G. Williams *et al.*, Phys. Rev. Lett. **93**, 261101 (2004).
[4] J. H. Taylor *et al.*, Nature (London) **355**, 132 (1992).

[5] I. H. Stairs *et al.*, Astrophys. J. **581**, 501 (2002).
[6] M. Kramer *et al.*, Science **314**, 97 (2006).
[7] T. Damour and G. Esposito-Farèse, Classical Quantum Gravity **9**, 2093 (1992).
[8] G. Esposito-Farese, in Proceedings of the Tenth Marcel Grossmann Meeting, 2005, p. 647.
[9] T. Damour, arXiv:0704.0749.
[10] I. H. Stairs, Living Rev. Relativity **6**, 5 (2003).
[11] V. M. Kaspi *et al.*, Astrophys. J. **543**, 321 (2000).
[12] S. M. Ord *et al.*, Mon. Not. R. Astron. Soc. **337**, 409 (2002).
[13] S. M. Ord *et al.*, Astrophys. J. Lett. **574**, L75 (2002).
[14] M. Bailes *et al.*, Astrophys. J. Lett. **595**, L49 (2003).
[15] A. W. Hotan *et al.*, Astrophys. J. **624**, 906 (2005).
[16] T. Damour and N. Deruelle, Ann. Inst. Henri Poincaré Phys. Théor. **44**, 263 (1986).
[17] T. Damour and J. H. Taylor, Phys. Rev. D **45**, 1840 (1992).
[18] T. Damour and J. H. Taylor, Astrophys. J. **366**, 501 (1991).
[19] T. M. Tauris and T. Sennels, Astron. Astrophys. **355**, 236 (2000).
[20] A. J. Faulkner *et al.*, Astrophys. J. Lett. **618**, L119 (2005).
[21] M. Bailes, arXiv:astro-ph/0702698.
[22] B. A. Jacoby *et al.*, Astrophys. J. Lett. **629**, L113 (2005).
[23] T. Damour and G. Esposito-Farèse, Phys. Rev. D **54**, 1474 (1996).