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SELF-CONSISTENCY OF RELATIVISTIC OBSERVABLES WITH GENERAL RELATIVITY IN THE WHITE DWARF–NEUTRON STAR BINARY PSR J1141−6545

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ABSTRACT

Here we report timing measurements of the relativistic binary PSR J1141−6545 that constrain the component masses and demonstrate that the orbital period derivative $\dot{P}_b = (-4 \pm 1) \times 10^{-13}$ is consistent with gravitational wave emission as described by the general theory of relativity. The mass of the neutron star and its companion are 1.30 ± 0.02 and $0.986 \pm 0.02\ M_\odot$, respectively, suggesting a white dwarf companion and extending the range of systems for which general relativity provides a correct description. On evolutionary grounds, the progenitor mass of PSR J1141−6545 should be near the minimum for neutron star production. Its mass is 2 standard deviations below the mean of the other neutron stars, suggesting a relationship between progenitor and remnant masses.

Subject headings: binaries: close — gravitational waves — pulsars: general — pulsars: individual (PSR J1141−6545) — relativity — stars: neutron

1. INTRODUCTION

Our knowledge of neutron star masses (Thorsett & Chakrabarty 1999) is derived largely from three relativistic binary pulsars with eccentric orbits and probable neutron star companions (Weisberg & Taylor 2003; Stairs et al. 2002; Deich & Kulkarni 1996). The masses of all known neutron stars exhibit a remarkably narrow scatter ($0.04\ M_\odot$) about their mean of $1.35\ M_\odot$. If one restricts attention to the neutron star pairs, the mean is $1.37\ M_\odot$. These binary pulsars have also been pivotal in tests of the general theory of relativity (Taylor, Fowler, & McCulloch 1979).

Gravitational waves have never been observed directly. Our best quantitative evidence for their existence comes from observations of the binary PSR B1913+16 (Damour & Taylor 1991). This pulsar has a negative orbital period derivative that is consistent with the emission of gravity waves at the 0.4% level. Unfortunately, the binary PSR B1534+12 is so close to the Earth that its proper motion induces a time-varying Doppler term into the timing that prevents separation of the relativistic contribution to the orbital period derivative from the kinematic one (Bell & Bailes 1996; Stairs et al. 2002). Until an independent distance can be established, this pulsar's orbital period derivative cannot verify the predictions of the theory to better than ~20%. Nevertheless, measurement of PSR B1534+12's post-Keplerian parameters have provided other tests of general relativity (Stairs et al. 2002), and binary pulsars such as PSR J0437−4715 have proved that the theory is consistently in agreement with the most precise observations (van Straten et al. 2001).

Discovered in the Parkes multibeam survey, PSR J1141−6545 is a 4.7 hr binary pulsar with an eccentricity of 0.17 that consists of a 394 ms relatively youthful pulsar of characteristic age ~1.4 Myr and an unidentified companion star. Early observations (Kaspi et al. 2000) of the periastron advance suggested a pulsar mass $M_p < 1.35\ M_\odot$, and a companion $M_c > 0.97\ M_\odot$. The observed tight distribution of neutron star masses near $1.35 \pm 0.04\ M_\odot$, where the quoted error reflects a Gaussian fit to the observed distribution, suggested that this system probably consisted of a $M_p \sim 1.3\ M_\odot$ neutron star and $M_c \sim 1\ M_\odot$ white dwarf companion. PSR J1141−6545 was therefore unique among the relativistic binary pulsars. Its component masses argued for a white dwarf companion, yet its orbit was highly eccentric making it the first of a new class of object. To date no white dwarf has been optically identified.

PSR J1141−6545 is an exciting target for timing. First, scintillation observations have demonstrated a clear modulation of the timescale of the interstellar "twinkling" allowing derivation of the system's angle of inclination and runaway velocity (Ord, Bailes, & van Straten 2002a). Two degenerate fits to the changing scintillation timescale were possible. The observed distribution of neutron star masses favored the solution with an inclination angle ($i = 76° \pm 2.°5$) and center of mass velocity in the plane of the sky of $V \sim 115$ km s^{-1}. These results provide an independent estimate of the system orientation to be compared with the timing. Second, neutral hydrogen observations (Ord, Bailes, & van Straten 2002b) have demonstrated that this pulsar is in a favorable location in the Galaxy where the observed orbital period derivative will, as in the case of PSR B1913+16, be dominated by the general relativistic contribution. Finally, contrary to PSR B1913+16, which is a very symmetric system with two neutron stars of nearly equal mass, PSR J1141−6545 is a very dissymmetric system as it comprises a strongly self-gravitating neutron star and a (relatively) weakly self-gravitating white dwarf. Timing this system therefore tests new aspects of relativistic theories of gravity (Damour & Esposito-Farèse 1992; Taylor et al. 1992; Arzoumanian 2003).

2. OBSERVATIONS AND DATA ANALYSIS

Observations of PSR J1141−6545 were conducted from 2001 January until 2003 February at the Parkes 64 m radio telescope as part of a scintillation study. The data from two orthogonal linear polarizations were detected and summed using a multichannel filterbank consisting of 2 × 512 × 0.5 MHz filters. These data were 1-bit sampled every 125 μs and written to magnetic tape for offline processing on the Swinburne University of Technology supercomputer. Observations were usually greater than one orbit in duration, and there were 10 sessions, nine of which took place in the 15 months prior to 2003 February. The central observing frequency was 1390 MHz, and total intensity pulse profiles were formed by folding the raw data at the topocentric period of the pulsar for integration times of 60 s.

A fit to the arrival times was made for the standard pulsar spin, astrometric, and Keplerian terms as well as three post-Keplerian parameters using a relativistic model (Damour & De-

TABLE 1
Observed and Derived Parameters

Parameter	Value
Right ascension, α (J2000)	11 41 07.022(6)
Declination, δ (J2000)	-65 45 19.089(9)
Pulse period, P (ms)	393.8978340370(2)
Reference epoch (MJD)	51369.8525
Dispersion measure (cm^3 pc^{-1})	116.048(2)
Period derivative, $\dot{P}$ ($\times 10^{-15}$)	4.294593(3)
Orbital period, P_b (days)	0.1976509587(3)
Projected semimajor axis, x (s)	1.85894(1)
Orbital eccentricity, e	0.171876(2)
Epoch of periastron, T_0 (MJD)	51369.854553(1)
Longitude of periastron, ω (deg)	42.457(2)
Number of arrival times	7180
rms residual (μs)	114
Damour-Deruelle PK parameters:	
γ (s)	0.00072(3)
$\dot{\omega}$ (deg yr^{-1})	5.3084(9)
$\dot{P}_b$ ($\times 10^{-12}$)	$-0.43(10)$
Damour-Deruelle GR fit:	
Companion mass, M_c ($M_\odot$)	0.986(20)
Pulsar mass, M_p ($M_\odot$)	1.30(2)
Sum of masses, M ($M_\odot$)	2.2883(6)
Derived parameter:	
Orbital inclination, i (deg)	$i > 75$

Notes.—Best-fit physical parameters and their formal 1 σ errors were derived from arrival time data by minimizing an objective function, as implemented in TEMPO (http://pulsar.princeton.edu/tempo). The timing model used is TEMPO's DD relativistic binary model (Damour & Deruelle 1986), which allows us to fit for $\dot{\omega}$, $\dot{P}_b$, and γ separately. To derive the best estimate of the companion and pulsar masses, a fit to only M and M_c was performed using TEMPO's DDGR model. This model assumes general relativity is correct. Parenthesized numbers represent the 1 σ uncertainty in the last digits quoted, and epochs are specified using the modified Julian day (MJD). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

ruelle 1986). After incorporation of archival timing data from the Australia Telescope National Facility archives from 1999 July to August we found that our measurements of the periastron advance $\dot{\omega}$, transverse Doppler and gravitational redshift, γ term, and orbital period derivative $\dot{P}_b$ became much more significant. These values are displayed in Table 1. The archival data consisted mainly of data taken with a 2 × 96 × 3 MHz filterbank system. We fitted for a single arbitrary offset between the two data sets to allow for the change in instrumentation.

3. INTERPRETATION

Newton's laws provide a relation between the system's masses and inclination angle i, and the common observables orbital period P_b and projected semimajor axis $x = (a \sin i)/c$. This is often referred to as the pulsar mass function f_P,

$$f_P = \frac{(M_c \sin i)^3}{M^2} = \left(\frac{2\pi}{P_b}\right)^2 \frac{(xc)^3}{G}, \tag{1}$$

where M is the sum of the masses, G is Newton's gravitational constant, and c is the speed of light. The quantities M_p and M_c refer to the mass of the pulsar and companion star, respectively.

General relativity allows us to use the post-Keplerian terms to derive component masses. The advance of periastron gives us the sum of the masses:

$$\dot{\omega} = 3\left(\frac{2\pi}{P_b}\right)^{5/3}\left(\frac{GM}{c^3}\right)^{2/3}(1-e^2)^{-1}. \tag{2}$$

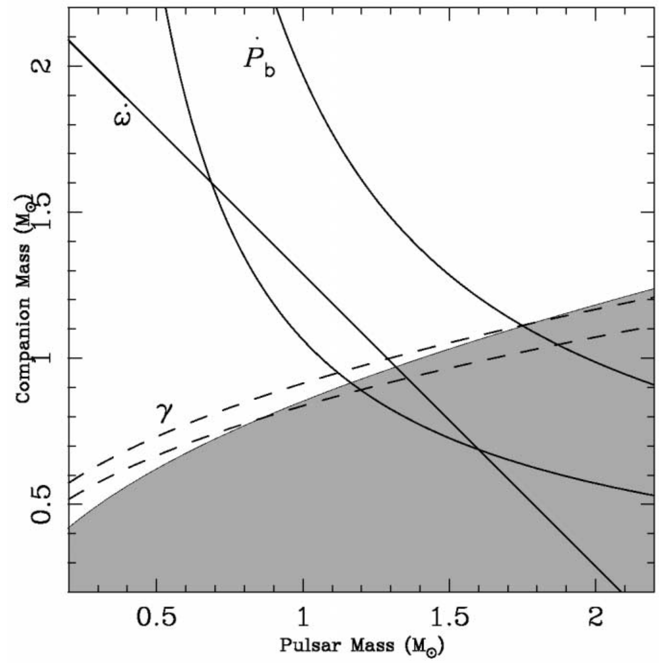

Fig. 1.—Constraints on the pulsar and companion masses. The shaded area is excluded from a consideration of Kepler's laws. The sum of the masses $M = 2.2883 \pm 0.0006\ M_\odot$ is very accurately defined from the relativistic advance of periastron, $\dot{\omega}$, and is shown by the straight solid line with a slope of -1. The relativistic term γ constrains the system to lie between the dashed lines, and the measured orbital period derivative $\dot{P}_b$ suggests that the system masses lie between the pair of curved solid lines. This implies an inclination angle $i > 75°$, consistent with constraints from scintillation studies $i = 76° \pm 2.5°$. The derived component masses suggest that the system consists of a $0.986 \pm 0.020\ M_\odot$ white dwarf and a $1.30 \pm 0.02\ M_\odot$ pulsar. If the system radiates energy at the rate predicted by general relativity, the measured orbital period derivative $\dot{P}_b = (-4 \pm 1) \times 10^{-13}$ is consistent with the predicted value of -3.8×10^{-13} derived from the component masses.

Here e is the orbital eccentricity. The combined transverse Doppler and gravitational redshift term gives a different relation between the masses:

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} G^{2/3} c^{-2} M_c (M_p + 2M_c) M^{-4/3}. \tag{3}$$

General relativity predicts that gravitational wave emission from binary systems removes energy that results in an orbital decay. The system is overdetermined if one can also measure the orbital period derivative $\dot{P}_b$:

$$\dot{P}_b = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{2\pi}{P_b}\right)^{5/3}(1-e^2)^{-7/2} \times \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) M_p M_c M^{-1/3}. \tag{4}$$

Thus, binary pulsars such as PSR J1141−6545 can be used to test the validity of the general theory of relativity. The allowed range of masses for the system are shown in Figure 1. Other post-Keplerian parameters such as the range and shape of the Shapiro delay were not significant in the fit.

The companion is almost certainly a white dwarf, unless neutron star masses extend over a very large range. The mean and standard deviation of the seven neutron stars shown in Figure 2 would place the companion of PSR J1141−6545

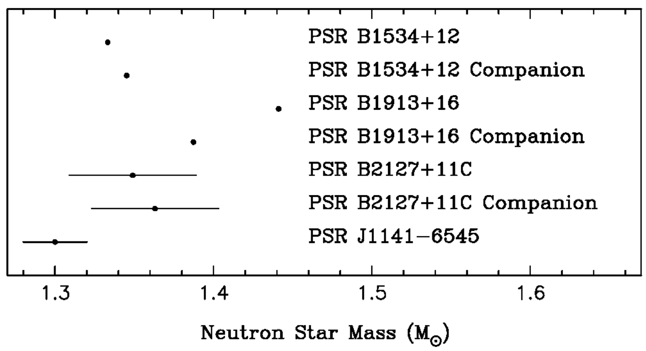

FIG. 2.—Neutron star masses derived from relativistic binary pulsars. Error bars are shown for all data, but in the case of PSR B1913+16 and PSR B1534+12 they are too small to be visible. Masses are taken from Deich & Kulkarni (1996), Stairs et al. (2002), and Weisberg & Taylor (2003). PSR J1141−6545 is the first neutron star not in a neutron star–neutron star binary to have its mass so precisely determined. On evolutionary grounds we know its progenitor was near the lower end of the mass distribution for pulsar progenitors. The low remnant mass suggests that the neutron star mass is related to that of the progenitor.

7 standard deviations from the mean of the others, which appears unlikely.

Young pulsars often exhibit significant timing noise, which makes timing proper motions unreliable on the timescale of a few years. A formal fit to the limited data yielded proper motions in both right ascension and declination of -12 ± 3 mas yr^{-1}. Whether the apparently 4 σ proper motion is real or not will become apparent with continued timing. For now we are treating the result with some caution. Timing noise has a much longer period (months to years) than the orbital period of our pulsar (4.7 hr), and so although the timing proper motion is potentially nonphysical, the derived orbital parameters are not subject to contamination by timing noise.

The self-consistency of the system with general relativity is very pleasing. The orbital period derivative is now a 4 σ result. The relative error in this term scales as the length of the observing span $t^{-5/2}$, so by the end of the decade it should be near 1%. PSR J1141−6545 is therefore likely to be a very important new testing ground for general relativity. The dissymmetry of the system tests different aspects of the theory since one of the stars is not strongly self-gravitating. Its favorable location in the Galaxy means that the measured orbital period derivative is close to the intrinsic value (Ord et al. 2002a). Unfortunately, the pulsar is young, and unlikely to be as intrinsically stable as PSR B1913+16, which has a much weaker magnetic field strength. Whether this is important or not for post-Keplerian orbital parameters remains to be seen. In any case, it will be difficult to surpass PSR B1913+16's relative errors on terms such as the relativistic contribution to the orbital period derivative.

4. DISCUSSION

Large-scale simulations of binary pulsar progenitors predict a large population of eccentric pulsar–white dwarf binaries (Tauris & Sennels 2000), albeit with a short observable lifetime. PSR J1141−6545 is thought to arise from the evolution of a binary in which both stars are initially less than the critical mass $M_{\rm crit}$ required to produce a supernova (Tauris & Sennels 2000). The initially more massive star transfers mass to its companion before becoming a white dwarf. If sufficient matter can be accreted by the initially lower mass star, it will exceed $M_{\rm crit}$ and produce a pulsar. Should the system remain bound, we will be left with a young neutron star orbiting a white dwarf companion in an eccentric orbit. PSR J1141−6545's mass M_p is therefore very important, because we know that the progenitor must have been less than $2M_{\rm crit}$–M_c. This is the first time we have an upper limit to the progenitor mass of a neutron star, albeit in terms of $M_{\rm crit}$. All previous neutron star mass measurements are from systems where both components were large enough to form neutron stars, which makes the progenitor masses far more difficult to constrain, as our theoretical understanding of the mass of neutron star progenitors is limited.

Radio pulsar masses cannot be easily determined. Neutron stars can theoretically exist over a range of masses (Timmes, Woosley, & Weaver 1996) that is much broader than that inferred from observations of radio pulsars (Weisberg & Taylor 2003; Stairs et al. 2002; Deich & Kulkarni 1996). Until these measurements, the mean and standard deviation of the six accurately known neutron stars was just $1.37 \pm 0.04\ M_\odot$. PSR J1141−6545's mass of 1.30 ± 0.02 is the smallest yet determined with any accuracy. Its mass is 2 standard deviations below the mean of the others as shown in Figure 2.

In the absence of any asymmetry in the explosion, component masses and orbital parameters define the progenitor system mass and runaway velocity (Radhakrishnan & Shukre 1986). If the explosion were symmetric, the presupernova star in the PSR J1141−6545 system would have been only $M_{\rm pre} = M(1+e) - M_c = 1.7\ M_\odot$. It seems unlikely that the presupernova star could be such a small fraction of its original mass of greater than $M_{\rm crit} \sim 8$–$11\ M_\odot$. Thus, PSR J1141−6545's orbital configuration is therefore a strong argument in favor of asymmetric supernova kicks (Dewey & Cordes 1987; Bailes 1989). Such kicks can misalign the spin and orbital angular momentum vectors of the pulsar, allowing detectable precession due to spin orbit coupling (Damour & Ruffini 1974; Barker & O'Connell 1975). This has been observed in the binary PSR 1913+16 (Kramer 1998). In PSR J1141−6545 the timescale for complete precession is only ∼200 yr. Its high orbital inclination could lead to significant changes in our line of sight to the pulsar's spin axis on the timescale of a decade or so. This might explain the nondetection of the pulsar in previous surveys of the region, and we would expect rapid evolution of the pulse profile as suggested by Kaspi et al. (2000).

PSR J1141−6545 is a very significant object. It has already validated scintillation speed methodologies, provided the first estimate of a neutron star mass where we have firm constraints on the progenitor, proved that mass transfer can transform a star that would otherwise become a white dwarf into a neutron star, and extended the range of systems for which general relativity provides an accurate description. Its orbital parameters suggest that the explosion was probably asymmetric. As the errors in orbital period derivative decrease, this system will test new aspects of theories of relativistic gravity that were impossible with the other relativistic binaries due to its unique composition (Taylor et al. 1992; Damour & Taylor 1992). Together, PSR B1913+16, PSR B1534+12, and PSR J1141−6545 will strongly constrain relativistic theories of gravity.

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REFERENCES

Arzoumanian, Z. 2003, in ASP Conf. Ser. 302, Radio Pulsars, ed. M. Bailes, D. J. Nice, & S. E. Thorsett (San Francisco: ASP), 69
Bailes, M. 1989, ApJ, 342, 917
Barker, B. M., & O'Connell, R. F. 1975, ApJ, 199, L25
Bell, J. F., & Bailes, M. 1996, ApJ, 456, L33
Damour, T., & Deruelle, N. 1986, Ann. Inst. H. Poincaré, 44, 263
Damour, T., & Esposito-Farèse, G. 1992, Classical Quantum Gravity, 9, 2093
Damour, T., & Ruffini, R. 1974, CR Acad. Sci. Paris, 279, 971
Damour, T., & Taylor, J. H. 1991, ApJ, 366, 501
———. 1992, Phys. Rev. D., 45, 1840
Deich, W. T. S., & Kulkarni, S. R. 1996, in IAU Symp. 165, Compact Stars in Binaries, ed. J. van Paradijs, E. P. J. van del Heuvel, & E. Kuulkers (Dordrecht: Kluwer), 279
Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780
Kaspi, V. M., et al. 2000, ApJ, 543, 321
Kramer, M. 1998, ApJ, 509, 856
Ord, S. M., Bailes, M., & van Straten, W. 2002a, MNRAS, 337, 409
———. 2002b, ApJ, 574, L75
Radhakrishnan, V., & Shukre, C. S. 1986, Ap&SS, 118, 329
Stairs, I. H., Thorsett, S. E., Taylor, J. H., & Wolszczan, A. 2002, ApJ, 581, 501
Tauris, T. M., & Sennels, T. 2000, A&A, 355, 236
Taylor, J. H., Fowler, L. A., & McCulloch, P. M. 1979, Nature, 277, 437
Taylor, J. H., Wolszczan, A., Damour, T., & Weisberg, J. M. 1992, Nature, 355, 132
Thorsett, S. E., & Chakrabarty, D. 1999, ApJ, 512, 288
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1996, ApJ, 457, 834
van Straten, W., Bailes, M., Britton, M., Kulkarni, S. R., Anderson, S. B., Manchester, R. N., & Sarkissian, J. 2001, Nature, 412, 158
Weisberg, J., & Taylor, J. H. 2003, in ASP Conf. Ser. 302, Radio Pulsars, ed. ed. M. Bailes, D. J. Nice, & S. E. Thorsett (San Francisco: ASP), 93