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PSR J1756−2251: A NEW RELATIVISTIC DOUBLE NEUTRON STAR SYSTEM

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ABSTRACT

We report the discovery during the Parkes Multibeam Pulsar Survey of PSR J1756−2251, a 28.5 ms pulsar in a relativistic binary system. Subsequent timing observations showed the pulsar to have an orbital period of 7.67 hr and an eccentricity of 0.18. They also revealed a significant advance of periastron, $2\overset{\circ}{.}585 \pm 0\overset{\circ}{.}002$ yr^{-1}. Assuming this is entirely due to general relativity implies a total system mass (pulsar plus companion) of $2.574 \pm 0.003\ M_\odot$. This mass and the significant orbital eccentricity suggest that this is a double neutron star system. Measurement of the gravitational redshift, γ, and an evaluation of the Shapiro delay shape, s, indicate a low companion mass of less than $1.25\ M_\odot$. The expected coalescence time due to emission of gravitational waves is only ~1.7 Gyr, substantially less than a Hubble time. We note an apparent correlation between spin period and eccentricity for normally evolving double neutron star systems.

Subject headings: pulsars: general — pulsars: individual (PSR J1756−2251)

1. INTRODUCTION

Relativistic double neutron star (DNS) binary systems in tight orbits are valuable physical laboratories, since their rapid evolution allows for stringent tests of gravitational theories in strong-field conditions (e.g., Taylor & Weisberg 1989). They make a significant contribution to estimated event rates for gravitational wave detectors (e.g., Kim et al. 2003). DNS binaries are rare since, even if the system survives the first supernova explosion, the progenitor system will typically disrupt with the second supernova explosion. Also, they are observationally selected against because of the large orbital modulation of the pulsar period. In this Letter, we report the discovery of PSR J1756−2251, a 28.5 ms pulsar, and present strong evidence that suggests that it is the eighth DNS binary system known and the fifth that will coalesce in less than a Hubble time. In § 2, we describe the observations, § 3 evaluates the nature of the companion, while § 4 discusses the search for a possible pulsar companion. Finally, § 5 considers some of the implications of the discovery.

2. OBSERVATIONS

PSR J1756−2251 was discovered in the Parkes Multibeam Pulsar Survey (PMPS; Manchester et al. 2001). The PMPS is the most successful survey for pulsars, with more than 700 pulsars discovered so far. The survey used a sensitive 13-beam receiver at the Parkes radio telescope to cover the Galactic plane ($|b| < 5°$, $260° < l < 50°$) with 35 minute integrations at a center frequency of 1374 MHz, with 96 frequency channels covering the 288 MHz bandwidth (BW), using 250 μs sampling.

An initial search using standard Fourier techniques, as described in Manchester et al. (2001), failed to detect PSR J1756−2251. The data were subsequently reanalyzed using an efficient acceleration code (Faulkner et al. 2004), and PSR J1756−2251 was detected in three beams, with the best signal-to-noise ratio of 19. The system was confirmed in 2003 June by reobservation at Parkes, using the "gridding" technique described in Morris et al. (2002).

PSR J1756−2251 has subsequently been observed regularly from Parkes at 1374 MHz using the 288 MHz BW and at 1390 MHz using the 256 MHz BW and 80 or 125 μs sampling time (t_s), plus occasional observations at 685 MHz (64 MHz BW; t_s: 80 μs) and 3030 MHz (768 MHz BW; t_s: 80 μs); at Jodrell Bank Observatory at 1396 MHz (64 MHz BW; t_s: 371 μs) and 610 MHz (4 MHz BW; t_s: 555 μs); and the Green Bank Telescope (GBT) at 1400 MHz (96 MHz BW; t_s: 72 μs) using the Berkeley Caltech Pulsar Machine (Backer et al. 1997). Full-orbit observations of ~8 hr have been made at Parkes and the GBT. Figure 1 shows the integrated pulse profile of PSR J1756−2251, at 1390 MHz with 512 kHz frequency channels and 80 μs sampling; it is sharp but featureless, with a pulse width of 2.7% of the spin period. The 1998 observations, with 3 MHz frequency channels, have higher dispersion smearing; however, the profile still appears similar. The profile at 3030 MHz is also similar while there is broadening at 685 MHz. Given that profile widths of recycled pulsars hardly evolve with frequency (Kramer et al. 1999), this broadening is likely to be a result of scattering. There is no evidence of any emission at phase 180° from the pulse.

For regular coverage over the orbit, pulse times of arrival (TOAs) were made using 10 minute subintegrations from the Parkes observations. Three survey observations, made 5 years before the confirmation, were included. The bulk of the observations, including 1189 of the 1382 timing points, were made at Jodrell Bank, each using 5 minutes of integration. The timing analysis used the TEMPO program[7] and gave the timing parameters listed in Table 1. PSR J1756−2251 is very close to the ecliptic plane, which has made the determination of its declination using timing measurements relatively imprecise.

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[7] See http://www.atnf.csiro.au/research/pulsar/tempo.

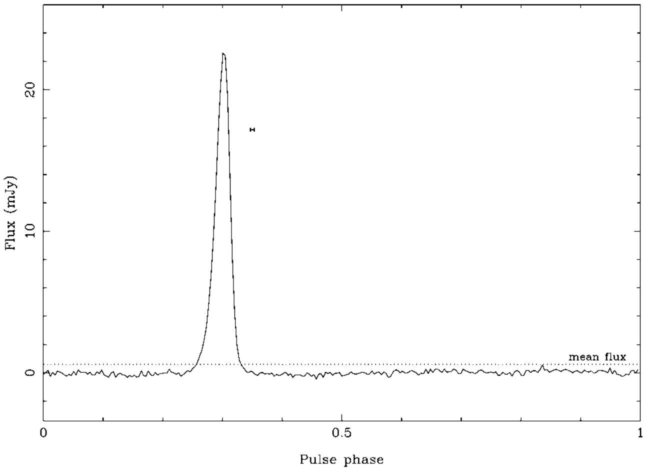

FIG. 1.—Average pulse profile of PSR J1756−2251 at 1390 MHz, obtained by integrating 27.9 hr of observation at Parkes. The small horizontal bar to the right of the pulse indicates the resolution of the profile, including the effects of interstellar dispersion

3. NATURE OF THE COMPANION

The masses of the pulsar and its companion cannot be measured independently in purely Keplerian orbits. However, the "mass function," $f_{\mathrm{mass}} = (m_2 \sin i)^3/(m_1 + m_2)^2$, can be found from the orbital period P_b and projected semimajor axis, $x = a_1 \sin i$, where i is the orbital inclination. This relates the masses of the pulsar, m_1, and the companion, m_2, both in solar masses. Since we fit for $0° \leq i \leq 90°$, clearly $\cos i$ must be greater than 0.

TABLE 1
OBSERVED AND DERIVED CHARACTERISTICS OF PSR J1756−2251

Parameter	Value
Right ascension (J2000.0)	$17^{\mathrm{h}}56^{\mathrm{m}}46\overset{\mathrm{s}}{.}6332(2)$
Declination (J2000.0)	$-22°51'59\overset{''}{.}4(2)$
Galactic longitude	$6\overset{\circ}{.}50$
Galactic latitude	$+0\overset{\circ}{.}95$
Ecliptic longitude	$+269\overset{\circ}{.}31$
Ecliptic latitude	$0\overset{\circ}{.}57$
Period, P	28.46158845494(2) ms
Period derivative, $\dot{P}$	$1.0171(2) \times 10^{-18}$
Epoch (MJD)	52,086
Dispersion measure, DM	121.18(2) pc cm^{-3}
Orbital period, P_b	0.319633898(2) days
Eccentricity, e	0.180567(2)
T_0 (MJD)	52,812.919653(1)
Longitude of periastron, ω	$322\overset{\circ}{.}571(4)$
Projected semimajor axis, $a_1 \sin i$	2.7564(2) lt-s
Advance of periastron, $\dot{\omega}$	$2\overset{\circ}{.}585(2)\ \mathrm{yr}^{-1}$
Gravitational redshift, γ	1.3(3) ms
Number of TOAs	1362
Timing data span (MJD)	50,996–53,176
rms timing residual	42 μs
Flux density at 1400 MHz	0.6(1) mJy
Width of pulse at 50%, W_{50}	0.78 ms
Width of pulse at 10%, W_{10}	1.6 ms
Characteristic age, τ_c	443 Myr
Surface magnetic field, B	5.4×10^9 G
Total system mass, $m_1 + m_2$	2.574(3) $M_{\odot}$
Pulsar mass, m_1[a]	$1.40^{+0.02}_{-0.03}$
Companion mass, m_2[a]	$1.18^{+0.03}_{-0.02}$
Time to coalesence (Gyr)	1.69 Gyr
Distance—NE2001	2.5 kpc
$\lvert z \rvert$	0.04 kpc

NOTES.—Values in parenthesis are twice the nominal TEMPO uncertainties in the least significant digits quoted, obtained after scaling TOA uncertainties to ensure $\chi^2 = 1$. Distance is estimated from the "NE2001" Galactic electron density model (Cordes & Lazio 2002).

[a] Pulsar and companion masses (1 σ errors) are derived from the DDGR model and are highly correlated.

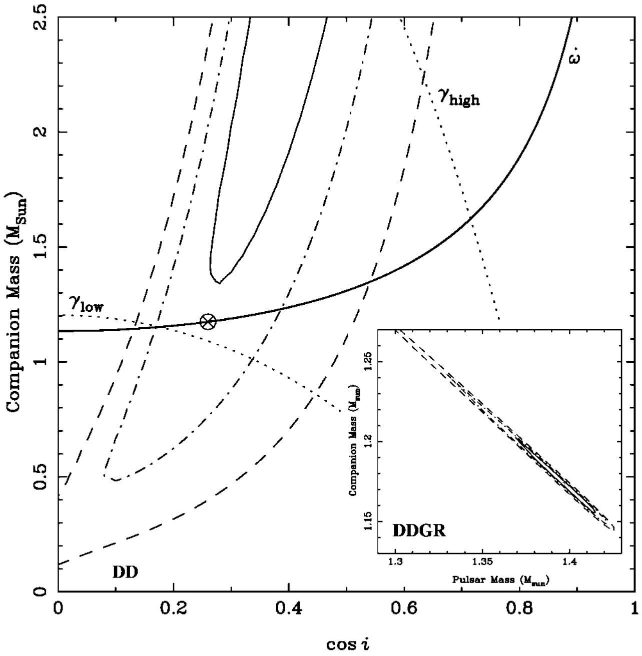

FIG. 2.—Observational constraints, using the DD model, on the companion mass and orbital inclination, i, shown as $\cos i$. The value of $\dot{\omega}$ is well constrained, and the solid line shows both the upper and lower limits of $\dot{\omega}$. The dotted lines show the much wider limits imposed by γ. Both $\dot{\omega}$ and γ errors are twice the formal TEMPO errors. The three contours show the 1 σ, 2 σ, and 3 σ ranges for a fixed Shapiro s parameter, and companion mass, with all other parameters left free. The inset shows a contour plot, also 1 σ, 2 σ, and 3 σ, of companion and pulsar masses using the DDGR model; see text for details. The best-fit companion mass found is shown as a cross on the main plot.

We have measured the precession of the longitude of periastron, $\dot{\omega}$, to be $2\overset{\circ}{.}585 \pm 0\overset{\circ}{.}002\ \mathrm{yr}^{-1}$. This could be due to a combination of tidal effects caused by a noncompact deformable companion (Smarr & Blandford 1976), the effects of relativistic gravitational interaction (Taylor & Weisberg 1989), or spin orbit coupling (e.g., Masters & Roberts 1975). Although it would be possible for a hydrogen main-sequence star to fit in the orbit, it would induce an $\dot{\omega}$ of ∼1000 times the observed value (see Masters & Roberts 1975). Alternatively, the companion could be a helium main-sequence star. Using the relationship between $\dot{\omega}$, m_1, and m_2 due to tidal effects derived in Roberts et al. (1976), we find that the required pulsar mass must be less than 0.6 $M_{\odot}$, which is very unlikely. Furthermore, there is no evidence of occultations of the pulsar, which is consistent with the companion's identification as a compact object. Hence, the companion must be a compact object: either a neutron star (NS) or white dwarf (WD). A fast-rotating WD could affect $\dot{\omega}$ by spin orbit coupling. Following Wex (1998), we estimated the size of the contribution from a derived upper limit on $\dot{x}/x$. While we do not know all relevant angles in the system's geometry, we conclude that this effect is insignificant, unless we observed the system under very specific angles and/or at particular phases of the orbital precession. While we consider this as unlikely, future observations will verify this conclusion.

Taking $\dot{\omega}$ to be entirely due to the effects of general relativity, the total system mass can be derived (see Damour & Taylor 1992). We obtain a value of $2.574 \pm 0.003\ M_{\odot}$. Figure 2 shows $\dot{\omega}$ as a function of m_2 and $\cos i$; the data were analyzed using the Damour-Deruelle (DD) model of TEMPO (Damour & De-

TABLE 2

BINARY SYSTEMS CONTAINING RADIO PULSARS THAT COALESCE IN LESS THAN 10^{10} yr

PSR	P (ms)	P_b (hr)	e	Total Mass ($M_\odot$)	τ_c (Myr)	$\tau_{\rm GW}$ (Myr)	Reference
J0737−3039A	22.70	2.45	0.088	2.58	210	87	Burgay et al. 2003
J0737−3039B	2773	2.45	0.088	2.58	50	87	Lyne et al. 2004
B1534+12	37.90	10.10	0.274	2.75	248	2690	Wolszczan 1990
J1756−2251	28.46	7.67	0.181	2.57	444	1690	This Letter
B1913+16	59.03	7.75	0.617	2.83	108	310	Hulse & Taylor 1975
B2127+11C	30.53	8.04	0.681	2.71	969	220	Anderson et al. 1990
J1141−6545†	393.90	4.74	0.172	2.30	1.4	590	Kaspi et al. 2000

NOTES.—One NS-WD (†) and five DNS systems. PSR B2127+11C is in a globular cluster, implying a different formation history to the Galactic DNS systems. Here τ_c is the pulsars' characteristic age and $\tau_{\rm GW}$ is the time remaining to coalesce due to emission of gravitational radiation. The total coalescence time is $\tau_c + \tau_{\rm GW}$.

ruelle 1985, 1986). The total system mass is remarkably similar to that of the double pulsar system J0737−3039 (2.588 $M_\odot$; Burgay et al. 2003).

The system mass, the age of the pulsar, and the significant eccentricity of 0.18 make a WD companion unlikely, since any accretion from the WD progenitor onto the NS would have circularized the orbit. If the companion is a WD, then it would be a CO type with a mass of ~1.2 $M_\odot$. At a distance of 2.5 kpc and assuming the pulsar characteristic age of 443 Myr, we expect it to be magnitude $\lesssim 24$ (e.g., Garćia-Berro et al. 1996). While it is probably too faint to be seen in available optical surveys, we have reviewed surveys and catalogs at the Astrophysical Virtual Observatory,[8] which includes objects with a maximum magnitude of 22.5. No plausible optical counterpart was found.

Although not yet well constrained, we have measured the gravitational redshift parameter, γ (Damour & Deruelle 1986), to be 1.3 ± 0.3 ms. This puts further limits on the masses as shown in Figure 2.

Measurements of the Shapiro delay parameters, range r and shape s, can provide estimates of both m_2 and i (e.g., Damour & Taylor 1992). It has not yet been possible to constrain r well, but constraints on s can be obtained by searching the χ^2 hypersphere, obtained by running TEMPO over a range of $\sin i$ and m_2 values. This further constraint is plotted as probability contours in Figure 2.

To constrain the masses of the pulsar and companion further, we can assume that general relativity is correct and apply the Damour-Deruelle General Relativity (DDGR) model (Taylor & Weisberg 1989). We have explored the χ^2 hypersphere of $m_1 + m_2$ and m_2, which are the only unknown parameters if the orbit is completely described by general relativity. A contour plot, of m_1 and m_2, is shown as an inset in Figure 2. This indicates a light NS companion, possibly with a mass similar to or lighter than that of PSR J0737−3039B (Lyne et al. 2004).

The expected value of the gravitational wave damping of the orbit is below our present detection limit. If we assume the pulsar has a mass 1.35 $M_\odot$, general relativity predicts a value for $\dot{P}_b$ of -2.2×10^{-15}.

4. COMPANION PULSAR SEARCH

PSR J1756−2251 probably followed a typical DNS evolution (e.g., Phinney & Kulkarni 1994). Both stars would initially have had masses greater than 8 $M_\odot$. The pulsar was formed in a supernova explosion of the more massive component. Subsequently, the companion expanded in its red giant phase and the pulsar accreted material, thus increasing its rotation rate. The two stars then spiralled together in a common envelope to give a tight orbit. Finally, the companion star exploded as a supernova.

The possibility that the companion star is also a pulsar has been explored. Any second pulsar would be highly accelerated, which would normally have the effect of reducing search sensitivity because of pulse smearing. However, we now know the precise orbital parameters and dispersion measure of PSR J1756−2251; we also know the ephemeris for a companion except for the projected semimajor axis, $a_2 \sin i$. This is dependent on the ratio of the masses of the two stars:

$$a_2 \sin i = \frac{m_1}{m_2} a_1 \sin i. \tag{1}$$

We are, therefore, able to make a fully coherent search for a companion pulsar using a series of values of m_2 appropriate to an NS. For each search, a time series in the pulsar rest frame was constructed by taking each time sample from the closest sample in the observation time series. Corrected time series from two full orbits of observations, at 1390 MHz from Parkes, were searched using the standard approach for a solitary pulsar (e.g., Manchester et al. 2001). PSR J0737−3039B is only visible for short periods at particular orbital phases (Lyne et al. 2004); consequently, searches were also conducted throughout the observation with a range of observation lengths from 10 minutes to the full orbit, with a limiting flux density of ~0.045 mJy. The process was repeated over a range of masses: $0.73m_1 < m_2 < 1.27m_1$. The searches were sensitive to spin periods from 1 ms up to 10 s.

Unfortunately, no companion pulsar was detected with a luminosity limit of ~0.3 mJy kpc^2, below that of the faintest known pulsar, which has a luminosity of 0.5 mJy kpc^2 (Camilo 2003).

5. DISCUSSION

Based on orbital damping due to emission of gravitational waves in general relativity (Peters & Mathews 1963), the coalescence time of PSR J1756−2251 is ~1.7 Gyr. This is substantially less than the age of the universe, and this system is therefore important in the estimation of coalesence rates of DNS systems.

General relativity predicts that the merging of two NSs will produce a burst of gravity waves (Misner et al. 1973) detectable over intergalactic distances by ground-based gravity-wave (GW) detectors. The pulsars predicted to coalesce within 10 Gyr are listed in Table 2.

The rate of mergers observable by GW detectors has been discussed extensively (see, e.g., Phinney 1991 and Kim et al. 2003). Following the discovery of PSR J0737−3039, predicted

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[8] See http://www.euro-vo.org.

NS-NS coalesce rates were substantially increased (Burgay et al. 2003; Kalogera et al. 2004). However, these calculations use only three systems: PSRs B1913+16, B1534+12, and J0737−3039A; PSR B2127+11C is usually not included in the calculations since it is in a globular cluster and probably formed by exchange interaction rather than binary evolution (Prince et al. 1991). The predicted rate of mergers is dominated by PSR J0737−3039A owing to its proximity, short time to coalesence, and difficulty of discovery due to Doppler smearing. Because its parameters are similar to those of known pulsars and it does not represent a new population, the addition of PSR J1756−2251 is not expected to make a significant difference to the predicted merger rate (Kalogera et al. 2004).

As noted by McLaughlin et al. (2005), for seven of the DNS systems known (excluding PSR B2127+11C; see above), there appears to be a strong correlation between spin period, *P*, and eccentricity, *e*, as shown by the dashed line in Figure 3. The Pearson correlation coefficient, *r*, for these seven systems is 0.97. A Monte Carlo simulation in which seven data points are drawn from a flat distribution in *P* and *e* show that such high values of *r* occur by chance only 0.1% of the time. This apparent correlation shows the current state of the DNS systems. The basic relationship between *P* and *e* was formed early in the system's history, with some evolution over the actual, but uncertain, age of the system.

Qualitatively, this relationship may be due to a less massive progenitor of the companion NS evolving through its giant phase relatively slowly, leaving a longer time to spin up the pulsar by accretion, hence a shorter spin period. Prior to the supernova explosion of the companion star, the orbit is expected to have been circularized as a result of accretion (e.g., Bhattacharya & van den Heuvel 1991). A less massive companion star will eject less mass from the explosion; hence, using the simplest symmetric mass-loss model that ignores kick velocities will result in a smaller recoil (Phinney & Kulkarni 1994). Hence, a less massive companion star will lead to a less eccentric DNS system as well as to a shorter spin period. There is a similar correlation between spin period and companion mass, further supporting this mechanism. A more detailed investigation of the various effects is clearly required.

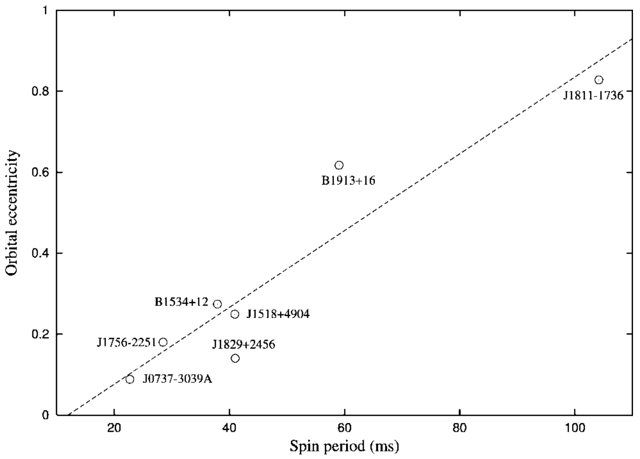

FIG. 3.—Plot showing the strong relationship between eccentricity and spin period of known DNSs. The dashed line is the best fit for all systems except PSR B2127+11C (not shown), which is likely to have a nontypical formation history.

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