An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system

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The merger[1] of close binary systems containing two neutron stars should produce a burst of gravitational waves, as predicted by the theory of general relativity[2]. A reliable estimate of the double-neutron-star merger rate in the Galaxy is crucial in order to predict whether current gravity wave detectors will be successful in detecting such bursts. Present estimates of this rate are rather low[3–7], because we know of only a few double-neutron-star binaries with merger times less than the age of the Universe. Here we report the discovery of a 22-ms pulsar, PSR J0737–3039, which is a member of a highly relativistic double-neutron-star binary with an orbital period of 2.4 hours. This system will merge in about 85 Myr, a time much shorter than for any other known neutron-star binary. Together with the relatively low radio luminosity of PSR J0737–3039, this timescale implies an order-of-magnitude increase in the predicted merger rate for double-neutron-star systems in our Galaxy (and in the rest of the Universe).

PSR J0737–3039 was discovered during a pulsar search carried out using a multibeam receiver[8] on the Parkes 64-m radio telescope in New South Wales, Australia. The original detection showed a large change in apparent pulsar period during the 4-min observation time, suggesting that the pulsar is a member of a tight binary system. Follow-up observations undertaken at Parkes consisting of continuous ~5-h observations showed that the orbit has a very short period (2.4 h) and a significant eccentricity (0.088). The derived orbital parameters implied that the system is relatively massive, probably consisting of two neutron stars, and predicted a huge rate of periastron advance $\dot{\omega}$ due to effects of general relativity. Indeed, after only a few days of pulse-timing observations we were able to detect a significant value of $\dot{\omega}$.

Interferometric observations made using the Australia Telescope Compact Array (ATCA) in the 20-cm band gave an improved position and flux density for the pulsar. Knowledge of the pulsar position with subarcsecond precision allowed determination of the rotational period derivative, $\dot{P}$, and other parameters from the available data span. Table 1 reports results derived from a coherent phase fit to data taken over about five months. The measured value of $\dot{\omega} = 16.88° \mathrm{yr}^{-1}$ is about four times that of PSR B1913+16 (ref. 9), previously the highest-known. If the observed $\dot{\omega}$ is entirely due to general relativity, it indicates a total system mass $M = 2.58 \pm 0.02 M_{\odot}$, where $M_{\odot}$ is the mass of the Sun.

Figure 1 shows the constraints on the masses of the pulsar and its companion resulting from the observations so far and the mean pulse profile as an inset. The shaded region indicates values that are ruled out by the mass function M_f and the observed $\dot{\omega}$ constrains the system to lie between the two diagonal lines. Together, these constraints imply that the pulsar mass m_p is less than $1.35 M_{\odot}$ and that the companion mass m_c is greater than $1.24 M_{\odot}$. The derived upper limit on m_p is consistent with the mass distribution of pulsars[10] in double-neutron-star systems. The minimum allowed companion mass implies that the companion is very likely also to be a neutron star.

This is supported by the observed significant eccentricity of the orbit, indicative of sudden and/or asymmetric mass loss from the system in the explosion when the companion collapsed[11]. Significant classical contributions to $\dot{\omega}$, either from tidal deformation[12] or rotation-induced quadrupole moment[13,14] in the companion—effects which might be present if it were not a neutron star—are therefore unlikely. In fact, $\dot{\omega}_{GR} \ll \dot{\omega}$ would imply an unacceptably low value for the pulsar mass. Hence this system probably contains two neutron stars with relatively low masses in the range 1.24–$1.35 M_{\odot}$, and the binary orbit is probably nearly edge-on (inclination, $i \approx 90°$). For $i = 68°$, the implied mass of the pulsar is $1.24 M_{\odot}$ and that of the companion is $1.35 M_{\odot}$.

A precise determination of the masses of both stars, and then of the orbital inclination, will be obtained when the gravitational redshift[9], γ, is measured. The expected minimum value (assuming an edge-on orbit) of this parameter is 383 μs. However, its orbital dependence is covariant with $a \sin i$ (Table 1) until there has been significant periastron precession. Whereas we currently get a formal value of $\gamma = 400 \pm 100$ μs from a fit of the timing data, a useful measurement of γ should be possible within a year.

Table 1 **Measured and derived parameters for PSR J0737–3039**

Right ascension (J2000)	07 h 37 min 51.28(2) s
Declination (J2000)	−30° 39′ 40.3(4)″
Galactic longitude	245.24°
Galactic latitude	−4.50°
Dispersion measure (pc cm^{-3})	48.9(2)
Flux density at 1,400 MHz (mJy)	6.9(6)
Flux density at 430 MHz (mJy)	100(20)
Period, P (ms)	22.69937854062(6)
Period derivative, $\dot{P}$ (s s^{-1})	2.3(6) × 10^{-18}
Epoch (MJD)	52800.0
Orbital period, P_b (days)	0.102251561(8)
Projected semi-major axis, $a\sin i$ (light s)	1.415176(5)
Eccentricity	0.087793(8)
Longitude of periastron, ω	68.743(9)°
Epoch of periastron, T_0 (MJD)	52760.807391(3)
Advance of periastron, $\dot{\omega}$ (° yr^{-1})	16.88(10)
Post-fit residual (μs)	33
Mass function, M_f ($M_{\odot}$)	0.291054(8)
Total system mass, M ($M_{\odot}$)	2.58(2)
Characteristic age, τ_c (Myr)	160(50)
Age since birth, τ_b (Myr)	100(50)
Surface dipole magnetic field strength, B (G)	7.3(9) × 10^{9}
Expected gravitational redshift parameter, γ (μs)	>383
Expected orbital period derivative (s s^{-1})	−1.24 × 10^{-12}

The pulsar position is obtained from observations made with the ATCA used in pulsar-gating mode. Uncertainties are given in parentheses and refer to the last quoted digit. The flux at 1,400 MHz is derived from the ATCA observations, while the flux at 430 MHz is obtained from Parkes observations with the flux value being derived from the observed signal-to-noise ratio and the estimated receiver sensitivity. Best-fit timing parameters are derived from arrival-time data by minimizing the χ^2 function using the program TEMPO (see http://pulsar.princeton.edu/tempo) with the relativistic binary model of ref. 27. For all the timing parameters except P_b, $\dot{\omega}$ and $\dot{P}$, uncertainties are twice the formal-fit 1σ error. Because of the short time span, $\dot{\omega}$ is strongly covariant with other orbital parameters and the nominal 1σ error resulting from the phase coherent fit of the pulse time-of-arrival might not represent the actual 1σ statistical uncertainty. By producing contours of constant χ^2 values as a function of P_b and $\dot{\omega}$, we have verified that an uncertainty of the order of four times the nominal 1σ error represents the uncertainty range for these parameters. The uncertainty in $\dot{P}$ is due to the residual covariance with the position terms resulting from the available uncertainty in the celestial coordinates obtained at the ATCA. The characteristic age τ_c and the surface dipole magnetic field strength B are derived from the observed P and $\dot{P}$ using the relations[28] $\tau_c = 0.5P/\dot{P}$ and $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$. The age since birth, τ_b, is the time since the binary pulsar left the spin-up line[4].

The parameters of the PSR J0737–3039 binary system, and the high timing precision made possible by the narrow pulses of this pulsar, promise to make this system an excellent 'laboratory' for the investigation of relativistic astrophysics, in particular of all the effects that are enhanced by a short orbital period, P_b. Geodetic spin-precession due to curvature of space-time around the pulsar is expected to have a period of 75 yr. This is four times less than the previously known shortest spin precession period and should allow detailed mapping of the pulsar emission beam[15] in a few years. It may also have the undesirable effect of making the pulsar undetectable in a short time.

The secular decay of the orbital period due to gravitational wave emission should be measurable within about 15 months. In PSR B1913+16, uncertainty in the orbital period derivative due to acceleration in the Galactic potential limits the precision of this test of the predictions of general relativity[16,17]. By comparison, PSR J0737–3039 is relatively close to the Sun and the uncertainty in Galactic acceleration will be much smaller, allowing a more precise test. Because of the probable high orbital inclination of the system, the delay due to the curvature of the space-time in the vicinity of the companion (the Shapiro delay[18]) should be measurable.

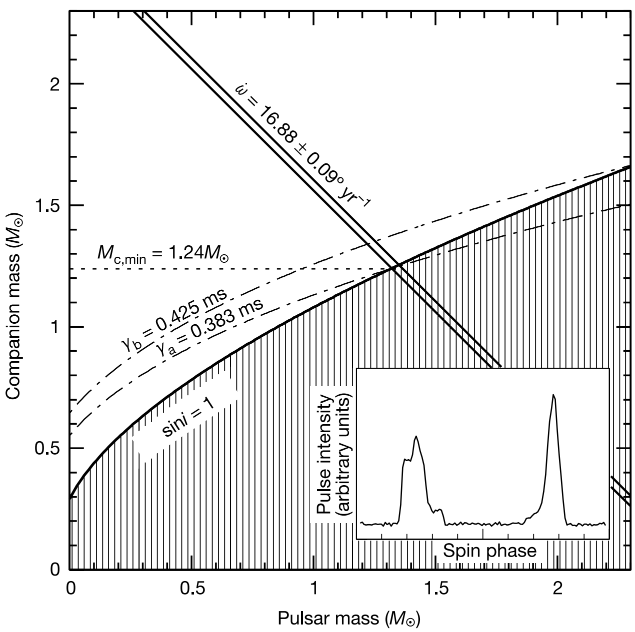

Figure 1 Constraints on the masses of the neutron star and the companion. The keplerian orbital parameters give the mass function:

$$M_f = \frac{(m_c \sin i)^3}{(m_c + m_p)^2} = \frac{4\pi^2 (a \sin i)^3}{G P_b^2} = 0.291054(8) M_\odot$$

where m_p and m_c are the masses of the pulsar and companion, P_b is the orbital period, and $a\sin i$ is the projected semi-major axis of the pulsar orbit; the estimated uncertainty in the last quoted digit is given in parentheses. This provides a constraint on the minimum m_c as a function of m_p by setting $i = 90°$, where i is the inclination of the orbit normal to the line of sight. In addition, assuming that the periastron advance rate $\dot{\omega}$ is entirely due to general relativity (that is, $\dot{\omega} = \dot{\omega}_{GR}$), its value can be combined with the other orbital parameters to determine the total system mass $M = m_c + m_p$ using the equation[27]:

$$m_c + m_p = \frac{P_b^{5/2}}{2\pi G} \left(\frac{(1 - e^2) c^2 \dot{\omega}}{6\pi} \right)^{3/2} = 2.58(2) M_\odot$$

where e is the orbital eccentricity. In the $m_c - m_p$ plane, the shaded region indicates the mass values ruled out by the mass function M_f, and the intersection of the boundary of this region with the $\dot{\omega}$ limits (defining a diagonal strip in the plot) provides a further constraint on the masses. The dash-dotted lines represent the mass values corresponding to the relativistic parameter γ for an edge-on orbit (γ_a) and for an orbital inclination $i = 68°$ (γ_b). The inset shows the mean pulse profile at 1,400 MHz from a 5-h observation. There are two pulse components separated by approximately half the 22-ms period.

The relatively small orbital eccentricity suggests that this system may have already undergone a substantial change of the orbital elements due to gravitational decay. Assuming that the evolution of orbital separation and eccentricity are entirely driven by gravitational radiation emission[19], and adopting a value of 100 Myr for the time elapsed since birth[4], τ_b (see Table 1), the orbital initially had a period of 3.3 h and an eccentricity of 0.119. Hence this system would already have experienced a ~25% decay of the orbital period and circularization, which would be the largest variation of these parameters in the sample of the known double-neutron-star binary systems.

Of the five double-neutron-star systems known so far[20], only three have orbits tight enough that the two neutron stars will merge within a Hubble time. Two of them (PSR B1913+16 and PSR B1534+12) are located in the Galactic field, while the third (PSR B2127+11C) is found on the outskirts of a globular cluster. The contribution of globular cluster systems to the Galactic merger rate is estimated to be negligible[21]. Also, recent studies[6] have demonstrated that the current estimate of the Galactic merger rate R relies mostly on PSR B1913+16. So, in the following discussion, we start by comparing the observed properties of PSR B1913+16 and PSR J0737–3039.

PSR J0737–3039 and its companion star will merge due to the emission of gravitational waves in $\tau_m \approx 85$ Myr, a timescale that is a factor of 3.5 shorter than that for PSR B1913+16 (ref. 9). In addition, the estimated distance of PSR J0737–3039 (500–600 pc, based on the observed dispersion measure and a model for the distribution of ionized gas in the interstellar medium[22]) is an order of magnitude less than that of PSR B1913+16. These properties have a substantial effect on the prediction of the rate of merging events in the Galaxy.

For a given class k of binary pulsars in the Galaxy, apart from a beaming correction factor, the merger rate R_k is calculated[6] as $R_k \propto N_k/\tau_k$. Here τ_k is the binary pulsar lifetime defined as the sum of the time since birth[4], τ_b, and the remaining time before coalescence, τ_m, and N_k is the scaling factor defined as the number of binaries in the Galaxy belonging to the given class. The shorter lifetime of PSR J0737–3039 ($\tau_{1913}/\tau_{0737} = (365\,\mathrm{Myr})/(185\,\mathrm{Myr}) \approx 2$, where the subscript numbers refer to the pulsars), implies a doubling of the ratio R_{0737}/R_{1913}. A much more substantial increase results from the computation of the ratio of the scaling factors N_{0737}/N_{1913}. The luminosity $L_{400} \approx 30\,\mathrm{mJy\,kpc^2}$ of PSR J0737–3039 is much lower than that of PSR B1913+16 (~200 mJy kpc^2). For a planar homogeneous distribution of pulsars in the Galaxy, the ratio $N_{0737}/N_{1913} \propto L_{1913}/L_{0737} \approx 6$. Hence we obtain $R_{0737}/R_{1913} \approx 12$. Including the moderate contribution of the longer-lived PSR B1534+12 system to the total rate[4–7], we obtain an increase factor for the total merger rate $(R_{0737} + R_{1913} + R_{1534})/(R_{1913} + R_{1534})$ of about an order of magnitude. A better estimate of this factor and its uncertainty can be obtained using a bayesian statistical approach and accounting for the full luminosity function of pulsars in the Galaxy[6].

Figure 2 displays an estimate of the probability density function for the merger rate increase factor, showing a peak value of ~8 and an upper limit of ~30 at a 95% confidence level. This result, derived in the simple assumption of a fixed pulsar luminosity and a uniform disk distribution of pulsar binaries, can be refined by including the parameters of the present survey into a simulation program modelling survey selection effects (and hence detection probability) and the Galactic population of pulsars. The Parkes high-latitude survey covers the region enclosed by Galactic latitude $|b| < 60°$ and Galactic longitude $220° < l < 260°$ for a total of 6,456 pointings, each of duration 265 s, using a bandwidth of 288 MHz and a sampling time of 125 μs. PSR J0737–3039 was detected with a signal-to-noise ratio of 18.7 in a standard Fourier search[23]. Variation in the apparent pulsar period due to binary motion during the discovery observation resulted in a 30% reduction in the observed signal-to-noise ratio.

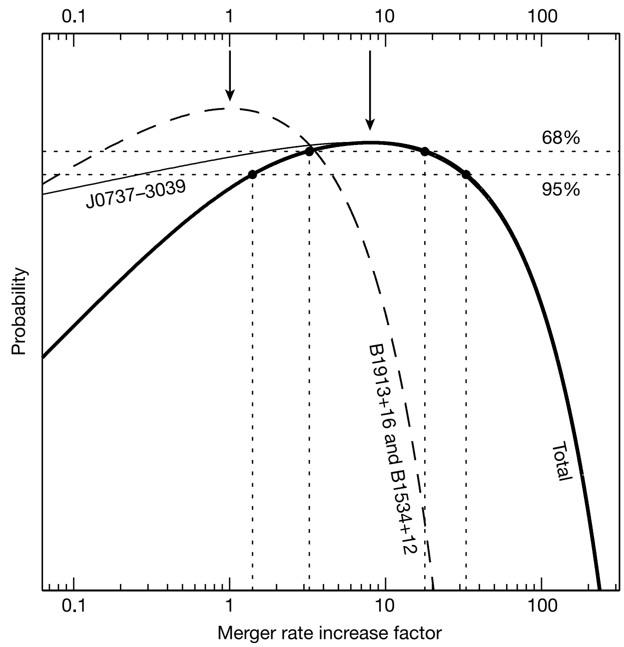

Figure 2 Probability density function for the increase in the double-neutron-star merger rate $(R_{0737} + R_{1913} + R_{1534})/(R_{1913} + R_{1534})$ resulting from the discovery of PSR J0737–3039. For a given class k of binary pulsars in the Galaxy, the probability density function $P(R_k)$ for the corresponding merger rate R_k is obtained from the relation[6] $P(R_k) = A^2 R_k e^{-AR_k}$ where $A = \tau_k/(N_k f_k)$, N_k is a population scaling factor (see text), τ_k is the binary pulsar lifetime and f_k is the correction factor due to the beamed nature of the radio pulsar emission. The dashed line represents the reference probability density function corresponding to the merger rate $R_{old} = R_{1913} + R_{1534}$ due to PSR B1913+16 and PSR B1534+12 only[6]. The heavy solid line represents the probability density function corresponding to the new merger rate $R_{new} = R_{0737} + R_{1913} + R_{1534}$. The parameters adopted for PSR J0737–3039 are those derived in the text ($N_{0737} = 6N_{1913}$, $\tau_{0737} = 185$ Myr) and the beaming factor for PSR J0737–3039, f_{0737}, is chosen as the average of the beaming factor of the other two known merging binaries ($f_{0737} = 1.06 f_{1913}$). The dotted vertical lines represent the 68% and 95% confidence level boundaries on the determination of the increase factor. The dominant role of PSR J0737–3039 in shaping the new statistics of the double-neutron-star merger rate is evident.

Extensive simulations (V.K. *et al.*, manuscript in preparation) produce results consistent with that derived in Fig. 2, and show that the peak of the merger rate increase factor resulting from the discovery of PSR J0737–3039 lies in the range 6 to 7 and is largely independent of the adopted pulsar population model. On the other hand, the actual predicted value of the Galactic merger rate and hence the detection rate by gravity wave detectors depends on the shape of the pulsar luminosity function. For the most favourable distribution model available (model 15 of ref. 6), the updated cosmic detection rate for first-generation gravity wave detectors such as VIRGO[24], LIGO[25] and GEO[26] can be as high as 1 every 1–2 yr at the 95% confidence level.

After a few years of operation of the gravity wave detectors, it should be possible to test these predictions directly and thus place better constraints on the cosmic population of double-neutron-star binaries. □

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Continuous magnetic reconnection at Earth's magnetopause

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The most important process that allows solar-wind plasma to cross the magnetopause and enter Earth's magnetosphere is the merging between solar-wind and terrestrial magnetic fields of opposite sense—magnetic reconnection[1]. It is at present not known whether reconnection can happen in a continuous fashion or whether it is always intermittent. Solar flares[2] and magneto-