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THE DOUBLE PULSAR SYSTEM J0737–3039

D. R. LORIMER
University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL UK

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The double pulsar system J0737−3039 – a 22.7 ms pulsar in a compact 2.4 hr orbit about a 2.7 s pulsar was one of the long-awaited "holy grails" of pulsar astronomy. After only two years of timing, the system is close to surpassing the original Hulse-Taylor binary as a test of general relativity. On-going timing should soon reveal second-order effects in the post-Newtonian parameters. In addition, the observed interactions of the radio beams of the two pulsars provide a unique laboratory for probing neutron star magnetospheres and relativistic winds. Finally, a revised estimate of the cosmic rate of double neutron star mergers including J0737−3039 boosts previous estimates by an order of magnitude and suggests a high detection rate for the advanced LIGO gravitational wave detector.

Keywords: pulsars; general relativity; plasma physics.

1. Discovery and basic properties of the J0737−3039 system

The first of the two pulsars, PSR J0737−3039A, was discovered in 2003 during a survey with the Parkes radio telescope.[1] This 22.7-ms pulsar (hereafter "A") was shown to be in a mildly eccentric ($e = 0.088$) 2.4 hr orbit about an (as then) unseen companion. From a measurement of the relativistic advance of periastron (see § 2) the total mass of the two stars $M = 2.59\ \mathrm{M}_\odot$ was determined. This and the other orbital characteristics strongly suggested that the orbiting companion is another neutron star as so far inferred in seven other binary pulsars.[2–8] The observable pulsars in these systems are thought to have obtained their short spin periods through the accretion of matter in an X-ray binary system.[9,10] The lack of any radio pulsations from their companions is probably reasonable given the much smaller radio beams and shorter radio lifetimes expected for the second-born pulsars.

The discovery of the second pulsar in this system, PSR J0737−3039B, came during routine timing observations at Parkes, where it was noticed that occasional 2.7-s pulsations were also present in the data. It was quickly established that this periodicity was modulated in exactly the manner expected based on the orbital parameters and, therefore, that the 2.7-s pulsar (hereafter "B") was the orbiting neutron star companion to A.[11] The ability to observe both pulsars as independent clocks yields the semi-major axes of each neutron star's orbit and, hence, the mass ratio of the two stars $R = m_A/m_B = 1.07$. Together, the measurements of M and R provide the masses of the two pulsars (see Table 1) and show that the orbital plane is almost perfectly aligned with our line of sight. As we shall see throughout this review, this rather unlikely viewing angle has important consequences.

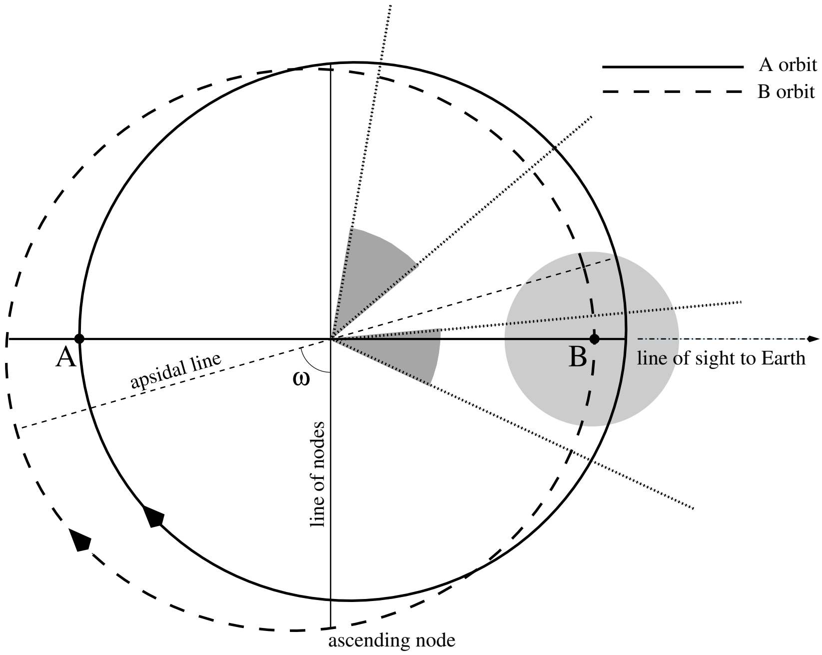

Fig. 1. Orbital plane of the binary system. The shaded regions are those orbital phases in which pulsar B is visible. Also shown is the size of B's magnetosphere relative to the orbit. Figure designed by Andrea Possenti.[11]

Table 1. Observed and derived parameters for the two pulsars using standard assumptions[12] for age, magnetic field, energy loss rate and light cylinder radius.

Parameter	Pulsar A	Pulsar B
Spin period, P (ms)	22.699	2773.5
Period derivative $\dot{P}$ ($\times 10^{-18}$ s/s)	1.74	880
Characteristic age, $\tau_c = P/(2\dot{P})$ (Myr)	207	50
Magnetic field, $B_s = 3.2 \times 10^{15} (P\dot{P})^{1/2}$ (T)	6.3×10^5	1.2×10^8
Energy loss rate, $\dot{E} = 3.95 \times 10^{39} \dot{P}/P^3$ (W)	5.9×10^{26}	1.6×10^{23}
Light cylinder radius, $r_{\rm LC} = cP/(2\pi)$ (m)	1.1×10^6	1.3×10^8
Orbital semi-major axis (m)	4.2×10^8	4.5×10^8
Mass ($M_\odot$)	1.348	1.249

The orbital geometry shown in Fig. 1 gives the relative size of the orbit to the magnetospheric boundaries of the two neutron stars. The size of the magnetosphere is limited by the "light cylinder radius" $r_{\rm LC}$ at which the co-rotation speed equals the speed of light.[12] As shown in the summary of relevant parameters of the two pulsars in Table 1, due to its longer spin period, B's magnetosphere is ~ 100 times that of A and 30% of the size of the orbit. With this large magnetosphere, and the near edge-on viewing geometry, it is not too surprising that we observe eclipses in A's emission at superior conjunction, as shown in Fig. 2. Also apparent is the rather sporadic emission from B. A systematic analysis[11] shows that B is only clearly visible over two orbital phase ranges marked in Fig. 1.

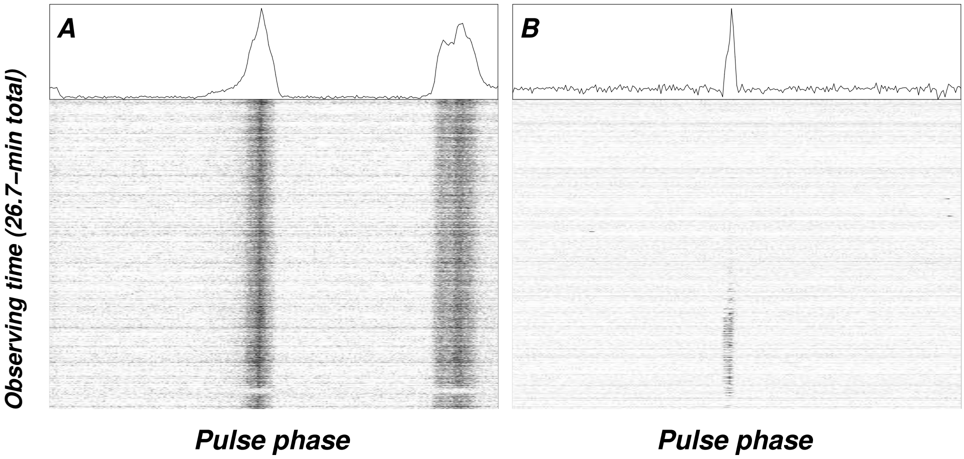

Fig. 2. Time series (grey scales) and integrated pulse profiles (top panels) of A and B from an 820-MHz Green Bank observation. The abrupt 30-s drop out in A's emission is caused by the occultation by B at superior conjunction. The time series for B shows sporadic emission as this pulsar competes against A's relativistic wind.

In the remainder of this article, we expand on this brief overview and summarise the current timing results and tests of general relativity (§ 2), discuss evidence for interactions (§ 3) and review the implications of this system for our understanding of the origin and evolution of binary pulsars (§ 4) and detection rates for gravitational wave detectors (§ 5).

2. Timing and tests of general relativity

In general, for any binary pulsar, at least five "Keplerian" parameters are required to fully describe a binary orbit: orbital period, P_b, projected semi-major axis, x, orbital eccentricity, e, angle of periastron, ω, and epoch of periastron, T_0. Constraints on the masses of the observable pulsar m_p and companion m_c can be placed from the mass function

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{x^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}, \qquad (1)$$

where G is Newton's constant and i is the angle between the orbital plane and the plane of the sky. For J0737−3039, where we observe two pulsar clocks, the ratio of both mass functions is the mass ratio of A and B, i.e. $R = f_B/f_A = m_A/m_B = 1.071 \pm 0.001$.

The compact orbit and strong gravitational fields of the two stars mean that a number of relativistic effects need to be taken into account. Already in A's discovery paper,[1] it was established that the relativistic periastron advance $\dot{\omega} = 16.9^\circ$ per year. In general relativity

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}, \qquad (2)$$

where $T_\odot \equiv GM_\odot/c^3 = 4.925490947\ \mu$s and the sum of the masses $M \equiv m_A + m_B$ is therefore 2.587 ± 0.001 M$_\odot$. Using this result, which assumes the correctness of Einstein's theory, and the mass ratio, we find $m_A = 1.338 \pm 0.001$ M$_\odot$ and $m_B = 1.249 \pm 0.001$ M$_\odot$.

Periastron advance is one of five additional "post-Keplerian" parameters required to describe a relativistic binary. The four remaining parameters, which have subsequently all been measured[13] for A, are: the time dilation and gravitational redshift parameter

$$\gamma_A = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_B (m_A + 2m_B), \tag{3}$$

the rate of orbital decay due to gravitational radiation

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_\odot^{5/3} m_A m_B M^{-1/3} \tag{4}$$

and the two Shapiro delay parameters

$$r_A = T_\odot m_B \tag{5}$$

and

$$s_A \equiv \sin i = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_B^{-1}, \tag{6}$$

which describe the delay in the pulses around superior conjunction where radiation from A is bent in the gravitational well of B. While in principle an equivalent set of equations can be written for B's orbit, in practice the longer spin period and sporadic emission of B mean that these effects will probably be impossible to measure.

Using the derived masses from the R and $\dot{\omega}$ measurements, we can perform four self consistency tests of general relativity by comparing the predicted values of γ_A, $\dot{P}_b$, r_A and s_A from Equations 3–6 with the observed values. These four tests all verify general relativity to within the measurement uncertainties. Currently the tightest constraint[13] is the Shapiro delay parameter s_A where observation and theory agree to within 0.1%.

In the two years since its discovery, the double pulsar system has already surpassed three decades of monitoring PSR B1913+16[14] and a decade of timing PSR B1534+12[15] as a test of general relativity. The relativistic effects observed in the double pulsar system are so large that corrections to higher post-Newtonian order may soon need to be considered. For example, $\dot{\omega}$, may be measured precisely enough to require terms of second post-Newtonian order to be included in the computations.[16] In addition, in contrast to Newtonian physics, general relativity predicts that the spins of the neutron stars affect their orbital motion via spin–orbit coupling. This effect would be visible clearest as a contribution to the observed $\dot{\omega}$ in a secular,[17] and periodic fashion.[18] For the J0737−3039 system, the expected contribution is about an order of magnitude larger than for PSR B1913+16.[11] As the exact value depends on the pulsars' moment of inertia, a potential measurement of this effect would allow the moment of inertia of a neutron star to be determined for the first time.[16] Such a measurement would be invaluable for studies of the neutron star 'equation-of-state' and hence our understanding of the behaviour of matter at extreme pressure and densities.[19]

3. Interactions between the two pulsars

As mentioned in § 1, there is significant observational evidence which shows that the radio beams of the two pulsars interact with each other. To understand why the pulsars should interact at all, let us briefly review the salient points concerning pulsar energetics. The rotation periods of all pulsars are observed to increase with time.[12] This spin down reflects the rate of loss of rotational kinetic energy of the spinning neutron star as it emits a 'wind', i.e. a stream of electromagnetic radiation along its emission beams. The relative spin properties of the neutron stars in the double-pulsar binary mean that their winds carry away energy at significantly different rates: the rate of loss of energy from A is some 3000 times greater than B (see Table 1). As a result, the energetics of A dominate this system.

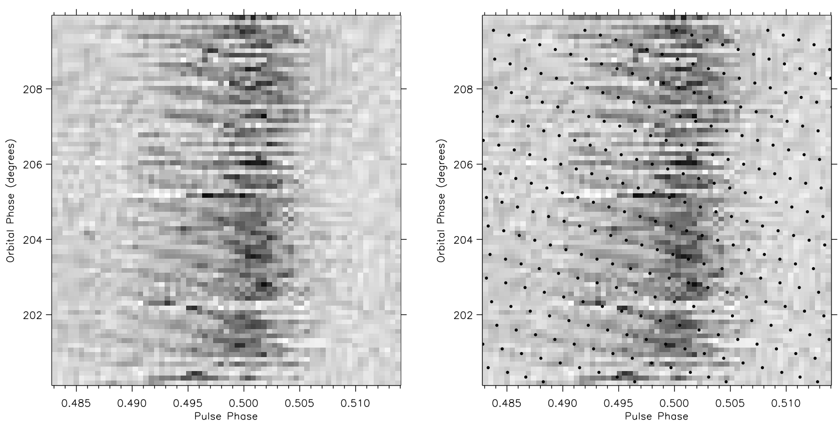

Fig. 3. Left: a sequence of single pulses from B shown as a function of orbital phase taken with the Green Bank telescope.[20] Right: the same data with arrival times of A's pulses in B's reference frame overlaid.

Striking evidence for the influence of the electromagnetic radiation from A impacting on B was found recently[20] and is presented in Fig. 3. In addition to the strong vertical band corresponding to the pulses of B, weaker diagonal sets of drifting pulses are clearly apparent. Although drifting subpulses of this kind are a well-studied phenomenon in isolated ("normal") pulsars,[21] due to processes in pulsar magnetospheres, two properties of these pulses strongly argue in favour of a different explanation here. Firstly, as shown in Fig. 1, they only occur at the orbital phase range when B is roughly perpendicular to our line of sight. Secondly, the drift rate of these pulses, 0.196 cycles per period, exactly matches the beat frequency of the two pulsar periods. As also shown in Fig. 3, the drifting bands closely follow the arrival time of A's pulses. This and the orbital phase range where these features are seen suggests that the simplest explanation for this phenomenon is that A's wind is buffeting B's magnetosphere into a comet-like structure which is most noticeable when viewed side-on, i.e. 44-Hz radiation from A is directly modulating the emission from B. In the second visibility phase, no modulations are expected as A's wind and B's magnetosphere are almost parallel to the line of sight.

Due to the near edge-on viewing geometry of the system, B's magnetosphere occults A and produces a 30-s eclipse in A's light curve[11,22] (Fig. 4). This is much shorter than a naïve estimate of 400 s from the size of B's light-cylinder radius (Table 1) and relative motion of A and B (660 km s^{-1}). The discrepancy is resolved when it is appreciated that the point of balance between the energy density of A's wind and B's magnetic energy density is only 10% of B's light cylinder radius.[11] This important result implies that A's wind penetrates deep into B's light cylinder and reducing the effective size of B's magnetosphere.

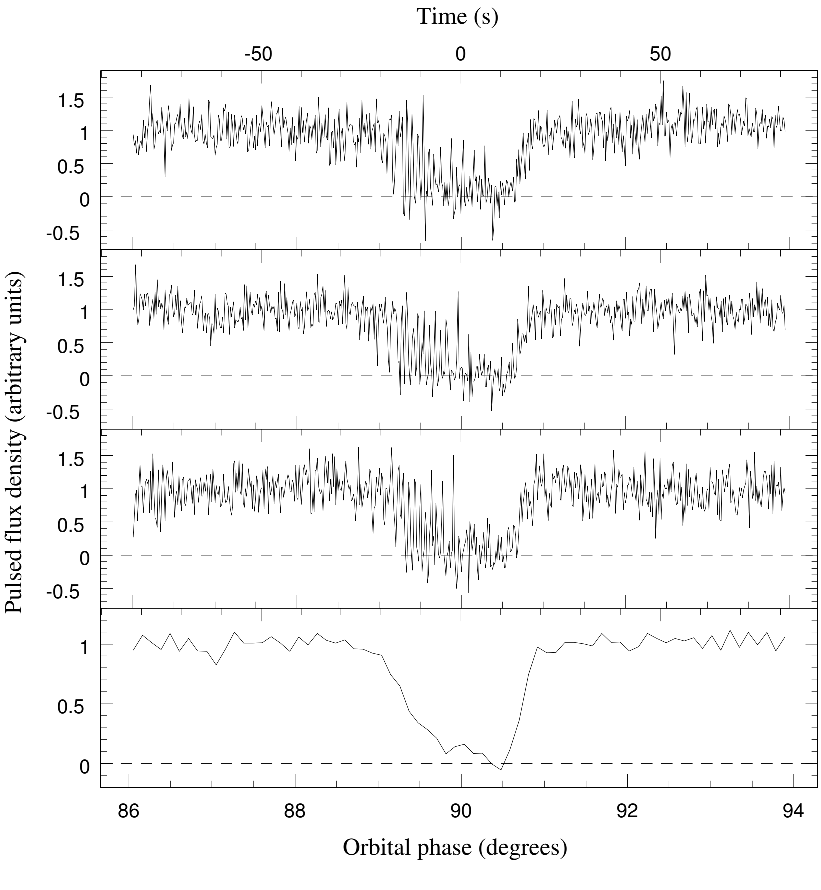

Fig. 4. Green Bank data[23] showing pulsed flux density of A versus time with respect to A's superior conjunction. Upper panels show the data based on averages of every 12 A periods. The lower panel shows all data summed and averaged over 100 A periods. The upper panels show a periodic flux modulation at exactly half B's period.

Perhaps more remarkably, as shown in the high-resolution eclipse light curves in Fig. 4, modulations in the pulsed flux density of A are seen at eclipse ingress.[23] A careful investigation of these modulations demonstrates that the modulation period is exactly half of B's spin period. This implies that the absorption of A's signal occurs twice as the two magnetic poles cross the line of sight during each B rotation. The interplay, shown schematically in Fig. 5, has many similarities with the Earth's magnetosphere and the Solar wind.

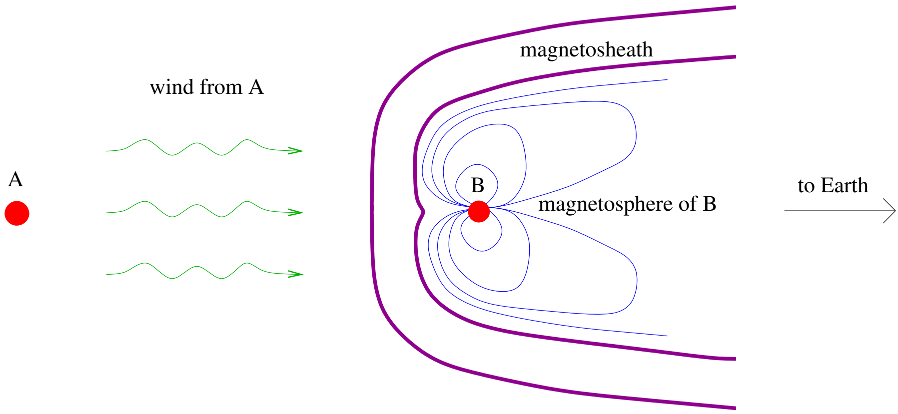

Fig. 5. Sketch (not to scale) showing the eclipse of A by B. Figure designed by Maura McLaughlin.[23]

4. Implications for the origin and evolution of binary pulsars

The existence of double neutron star binaries can be understood by a binary evolution scenario which starts with two main sequence stars.[10] The initially more massive star evolves first and eventually explodes in a supernova to form a neutron star. Under favourable conditions, this neutron star remains bound to its companion and spins down as a normal pulsar for the next $10^6 - 10^7$ yr. At some later time, the remaining (secondary) star comes to the end of its main-sequence lifetime and begins a red giant phase. Depending on the orbital parameters of the system, the strong gravitational field of the neutron star attracts matter from the red giant, forming an accretion disk and making the system visible as an X-ray binary. The accretion of matter transfers orbital angular momentum to the neutron star, spinning it up to short periods and dramatically reducing its magnetic field.[24] A limiting spin period is reached due to equilibrium between the magnetic pressure of the accreting neutron star and the ram pressure of the infalling matter.[10,25]

A crucial phase in the evolution of close double neutron star binaries like J0737−3039 is the dramatic reduction in orbital separation that occurs when matter from the secondary star is expelled from the system, resulting in a very compact system consisting of a helium star and a neutron star.[26,27] A sufficiently massive helium star will ultimately undergo a supernova explosion forming a young, second neutron star. If the stars remain bound following this explosion, the resulting system is a pair of neutron stars in an eccentric orbit with very different magnetic field strengths and hence spin-down properties, as in fact observed here. We note however, that due to the penetration of A's wind into B's light cylinder mentioned in the previous section some care should be taken when interpreting the exact value of B's magnetic field. A model has been proposed[28,29] in which A's wind exerts a propeller torque on B which dominates its spindown. In this case, the implied magnetic field strength of B is a factor of three lower than the dipole estimate in Table 1.

From the masses of the pulsar pair quoted in Table 1, A appears to be typical of other neutron stars with measured masses,[30] while B has a significantly smaller mass than any other. Although the masses of A and B are significantly different this is not a direct consequence of the accretion process. Accretion onto A at the Eddington rate is only expected to be of order 6×10^{-4} $M_\odot$.[31] It is more likely that the mass difference indicates a broader neutron star mass distribution than previously thought.[30]

The time since the second supernova explosion can be estimated by comparing our measurements of P and $\dot{P}$ for A and B, which can be used to compute their characteristic ages $\tau = P/(2\dot{P})$. If characteristic ages are good indicators of pulsars' true ages, we expect $\tau_A = \tau_B$, but the observed values are $\tau_A = 4.1\tau_B$. This discrepancy can be reconciled by questioning one or more of the assumptions inherent in the use of characteristic ages as estimates of true ages: a negligible birth spin period and a non-decaying magnetic dipole braking torque. At the very least, the post-accretion spin period of A cannot have been negligible due to details of the accretion process discussed above. Simple models assuming constant magnetic dipole spin-down[32] predict a post-accretion spin period for A in the range $10-18$ ms, enough to explain the observed discrepancy in the characteristic ages. This initial spin period range is consistent with the limiting spin period predicted by simple accretion theory.[25] Work now in progress attempts to improve constraints on the initial system parameters using a model for the interaction of A on B.[33]

5. Binary coalescence and implications for gravity wave detectors

PSR J0737$-$3039 will coalesce due to the emission of gravitational waves in 85 Myr. If a similar event occurs in the local Universe within the next few years, current gravitational wave detectors[34] would detect the final moments of inspiral and the ensuing merger. The cosmic rate of double neutron star mergers, then, is of great importance to current and future detectors. Only four of the eight currently known double neutron star systems will merge within a Hubble time and contribute significantly to the Galactic merger rate, $\mathscr{R}$. The general approach to determine $\mathscr{R}$ is a Monte Carlo analysis[35] which accounts, as far as possible, for known selection effects in the observed sample.

The results of the most recent study of this kind,[36,37] which take into account the discovery of PSR J0737$-$3039, are summarised in Fig. 6. The combined Galactic merger rate, dominated by the double pulsar, is found to be $\mathscr{R} = 80^{+210}_{-70}$ Myr^{-1}, where the uncertainties reflect the 95% confidence level using a Bayesian analysis.[35] Extrapolating this number out to include double neutron star binaries detectable by LIGO in other galaxies,[38] the expected event rate is $35^{+90}_{-30} \times 10^{-3}$ yr^{-1} for initial LIGO and 190^{+470}_{-150} yr^{-1} for advanced LIGO. Future prospects for detecting gravitational-wave emission from binary neutron star inspirals are therefore very encouraging. As much of the uncertainty in the rate estimates is due to our ignorance of the underlying distribution of double neutron star systems, future detection rates could ultimately constrain the properties of this exciting binary species.

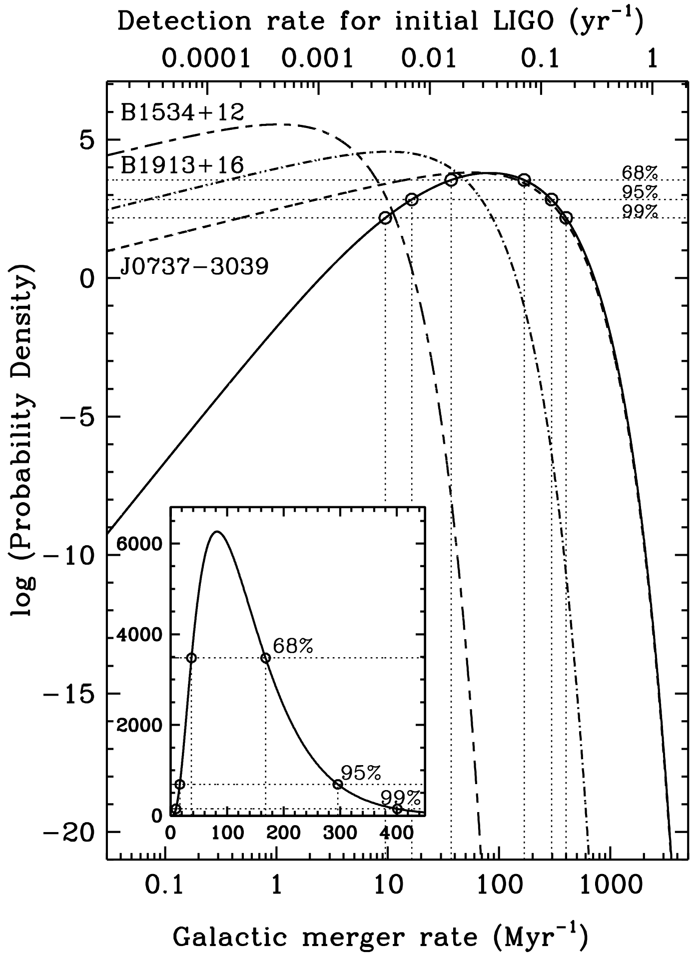

Fig. 6. The derived probability density function[37] that represents our expectation that the actual double neutron star binary merger rate in the Galaxy (*bottom axis*) and the predicted initial LIGO rate (*top axis*) take on particular values. The curves shown are calculated assuming a reference model.[36] The solid line shows the total probability density along with those obtained for each of the three binary systems (*dashed lines*). *Inset*: Total probability density, and corresponding 68%, 95%, and 99% confidence limits, shown in a linear scale.

Acknowledgements

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References

1. M. Burgay *et al.*, *Nature* **426**, 531 (2003).
2. R. A. Hulse and J. H. Taylor, *Astrophys. J.* **195**, L51 (1975).
3. A. Wolszczan, *Nature* **350**, 688 (1991).
4. T. A. Prince, S. B. Anderson, S. R. Kulkarni and W. Wolszczan, *Astrophys. J.* **374**, L41 (1991).
5. D. J. Nice, R. W. Sayer and J. H. Taylor, *Astrophys. J.* **466**, L87 (1996).
6. A. G. Lyne *et al.*, *Mon. Not. Roy. Astron. Soc.* **312**, 698 (2000).
7. D. J. Champion *et al.*, *Mon. Not. Roy. Astron. Soc.* **350**, L61 (2004).
8. A. J. Faulkner *et al.*, *Astrophys. J.* **618**, L119 (2005).
9. M. A. Alpar, A. F. Cheng, M. A. Ruderman and J. Shaham, *Nature* **300**, 728 (1982).
10. D. Bhattacharya and E. P. J. van den Heuvel, *Phys. Rep.* **203**, 1 (1991).
11. A. G. Lyne *et al.*, *Science* **303**, 1153 (2004).
12. D. R. Lorimer and M. Kramer, *Handbook of Pulsar Astronomy*, Cambridge University Press (2005).
13. M. Kramer *et al.*, in preparation (2005).
14. J. Weisberg and J. H. Taylor, in *Binary Pulsars*, eds. F. A. Rasio and I. H. Stairs, 25 (2005).
15. I. H. Stairs, S. E. Thorsett, J. H. Taylor and A. Wolszczan, *Astrophys. J.* **581**, 501 (2002).
16. T. Damour and G. Schäfer, *Nuovo Cim.* **101**, 127 (1988).
17. B. M. Barker and R. F. O'Connell, *Phys. Rev.* **D12**, 329 (1975).
18. N. Wex, *Class. Quantum Grav.* **12**, 983 (1995).
19. J. Lattimer and M. Prakash, *Science* **304**, 536 (2004).
20. M. A. McLaughlin *et al.*, *Astrophys. J.* **613**, L57 (2004).
21. J. H. Taylor, R. N. Manchester and G. R. Huguenin, *Astrophys. J.* **195**, 513 (1975).
22. V. M. Kaspi *et al.*, *Astrophys. J.* **613**, L137 (2004).
23. M. A. McLaughlin *et al.*, *Astrophys. J.* **616**, L131 (2004).
24. N. Shibazaki, T. Murakami, J. Shaham and K. Nomoto, *Nature* **342**, 656 (1989).
25. Z. Arzoumanian, J. M. Cordes and I. Wasserman, *Astrophys. J.* **520**, 696 (1999).
26. E. P. J. van den Heuvel and C. de Loore, *Astron. Astrophys.* **25**, 387 (1973).
27. B. P. Flannery and E. P. J. van den Heuvel, *Astron. Astrophys.* **39**, 61 (1975).
28. M. Lyutikov, *Mon. Not. Roy. Astron. Soc.* **353**, 1095 (2004).
29. J. Arons, D. C. Backer, A. Spitkovsky and V. M. Kaspi, in *Binary Pulsars*, eds. F. A. Rasio and I. H. Stairs, 95 (2005).
30. S. E. Thorsett and D. Chakrabarty, *Astrophys. J.* **512**, 288 (1999).
31. J. D. M. Dewi and E. P. J. van den Heuvel, *Mon. Not. Roy. Astron. Soc.* **349**, 169 (2004).
32. D. R. Lorimer *et al.*, in *Binary Pulsars*, eds. F. A. Rasio and I. H. Stairs, 113 (2005).
33. D. R. Lorimer *et al.*, in preparation (2005).
34. B. F. Schutz, in *Pulsar Astronomy – 2000 and Beyond*, eds. M. Kramer, N. Wex and R. Wielebinski, 727 (2000).
35. C. Kim, V. Kalogera and D. R. Lorimer, *Astrophys. J.* **584**, 985 (2003).
36. V. Kalogera *et al.*, *Astrophys. J.* **601**, L179 (2004).
37. V. Kalogera *et al.*, *Astrophys. J.* **614**, L137 (2004).
38. E. S. Phinney, *Astrophys. J.* **380**, L17 (1991).