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# A Review of The Double Pulsar - PSR J0737−3039

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**Abstract** J0737−3039 is the recently-discovered, first-known double-pulsar binary, a very compact double neutron star system in which both stars are observable as radio pulsars. In this review, we briefly describe the discovery and the studies which have been enabled by the unique properties of the system. These range from the most precise confirmation yet of the theory of general relativity, with the possibility of even more new tests and the measurement of second-order post-Newtonian effects, to studies of the magnetospheres and emission properties of the two pulsars. The discovery also resulted in a significant increase in the expected rate of occurrence of the mergers of double neutron star systems, and hence the likely rate of detection of such events by the new ground-based gravitational wave detectors.

**Key words:** pulsars: individual (PSR J0737−3039) — gravitation — plasmas

## 1 INTRODUCTION

The double-pulsar binary system J0737−3039 was discovered during a high galactic latitude survey using a multibeam receiver on the Parkes 64-m radiotelescope (Manchester et al. 2001). The first of the two pulsars to be discovered was J0737−3039A (hereafter A), a 22.7-millisecond pulsar (Burgay et al. 2003). The period of the pulsar was seen to be changing rapidly, even within the short 4-minute discovery observation. This immediately suggested that it was accelerating in the strong gravitational field of a companion star. Subsequent observations in early 2003 showed that it was in a 2.4-hour, mildly eccentric (e = 0.088) orbit. Within a few days, it was found that the longitude of periastron was increasing at a rate of 17.88 degrees/year. Interpreted as arising from general relativity, this value indicated that the system had a total mass of about 2.6 solar masses, suggesting that the second pulsar might also be a neutron star, albeit rather less massive than previously determined neutron star masses.

The data recorded during these initial measurements were searched for the presence of pulses from a companion pulsar but none were seen. However, in October 2003 a 40-min observation revealed a brief 10-minute burst of pulses having a repetition period of 2.77 seconds. Further investigations revealed that these pulses showed the Doppler variations in period appropriate for a pulsar companion to the millisecond pulsar, demonstrating incontrovertibly that this second pulsar, J0737−3039B (hereafter B), was indeed the companion, and of course that it was another neutron star (Lyne et al. 2004). This pulsar was found to be radiating strongly only for two intervals of about 10 minutes during the 2.4-hour orbit. Moreover, these "bright" intervals always occurred at exactly the same orbital longitude. Much weaker radiation could also be seen at other longitudes.

The properties of the system are summarized in Table 1. A has the typical period, magnetic field ($6\times10^9$ G) and characteristic age (210 Myr) of a millisecond pulsar, while the 2.77-s period pulsar, B, has the basic properties of a relatively young, unrecycled pulsar, having a magnetic field of $2\times10^{12}$ G and a characteristic age of 50 Myr. It is believed that the evolutionary sequence of the system is that of classical double neutron-star formation (e.g. Bhattacharya & van den Heuvel 1991) in which the more massive of two orbiting massive main-sequence stars evolves to its red-giant phase. This is followed by the collapse of its core to a neutron star in a subsequent supernova explosion. The "kick" from the explosion must have

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**Table 1** Basic Observed Parameters of PSRs J0737−3039A and B

| Pulsar | PSR J0737−3039A | PSR J0737−3039B |
|---|---|---|
| Pulse period $P$ | 22.7 ms | 2.77 s |
| Period derivative $\dot{P}$ | $1.7 \times 10^{-18}$ | $0.88 \times 10^{-15}$ |
| Orbital period $P_{\rm b}$ | 2.45 hours | |
| Eccentricity $e$ | 0.088 | |
| Orbital inclination | ∼88 deg | |
| Projected semi-major axis $x$ | 1.42 sec | 1.51 sec |
| Stellar mass $M$ | 1.337(5) $M_{\odot}$ | 1.250(5) $M_{\odot}$ |
| Mean orbital velocity $V_{\rm orb}$ | 301 km s$^{-1}$ | 323 km s$^{-1}$ |
| Characteristic age $\tau$ | 210 Myr | 50 Myr |
| Magnetic field at surface $B$ | $6.3 \times 10^{9}$ G | $1.2 \times 10^{12}$ G |
| Radius of Light cylinder $R_{\rm LC}$ | 1080 km | 132 000 km |
| Spin-down luminosity $\dot{E}$ | $6000 \times 10^{30}$ erg s$^{-1}$ | $1.6 \times 10^{30}$ erg s$^{-1}$ |

been insufficient in size to disrupt the binary and so a young pulsar is left orbiting the second main-sequence star. Eventually, the second star enters its own red-giant phase followed by a period of accretion of matter onto the neutron star during which the latter spins up to millisecond rotation period. The core of the second star then collapses to another neutron star accompanied by a further supernova explosion which again fails to disrupt the binary, leaving a young pulsar, B, in orbit with a millisecond pulsar, A.

There are four main aspects of this system which offer the possibility of new advances in physics and astrophysics and we address each of these areas in turn:

- New and more precise tests of gravitation theory than have been possible before.
- The decay of the orbit due to the emission of gravitational radiation, implying an increased frequency of occurrence of DNS coalescence events which might be detected by terrestrial gravitational wave detectors.
- The impact of energy from the millisecond pulsar A on the magnetosphere of B, causing both rapid and long-term modulation of the radio emission from B.
- The eclipse of the radio emission from A by the magnetosphere of B.

## 2 TESTS OF GRAVITATIONAL THEORY

Non-relativistic binary systems are usually precisely described by the five Keplerian parameters, $P_{\rm orb}$, $a\sin i$, $e$, $\omega$ and T$_o$ and these are all accurately measured when one object is a pulsar. However, a number of general relativistic corrections to this classical description of the orbit - the so-called post-Keplerian (PK) parameters - are needed if the gravitational fields are sufficiently strong. In only a few months, using the Parkes Telescope, the Lovell Telescope at Jodrell Bank and the Green Bank Telescope, it was possible to measure several general relativistic effects in 6 months that took years to measure with the Hulse-Taylor binary pulsar, PSR B1913+16.

The following five PK relativistic parameters have already been measured in A, all causing small, but highly significant, modifications to the arrival times of the pulsars' radio pulses:

**Relativistic periastron advance, $\dot{\omega}$.** This is the rotation of the line connecting the two pulsars at their closest approach to one another. It arises from the distortion of space-time caused by the two stars, but can also be understood as the result of the finite time needed for the gravitational influence of one star to travel to another. This causes a time delay, during which the stars move so that the attractive force is no longer radial.

**Gravitational redshift and time dilation, $\gamma$.** The redshift results in clocks appearing to run slowly in a gravitational potential well and time dilation is the special relativistic effect which results in moving clocks appearing to run slowly. Both effects cause clocks close to a neutron star to tick more slowly than those further away. In other words the apparent pulse rate for A will slow down when it is close to B, and vice versa.

**Shapiro delay, $r$ and $s$.** Radiation passing close to a massive body is delayed because its path length is increased by the curvature of space-time, an effect that Einstein overlooked but that was discovered in

1964 by Irwin Shapiro (Shapiro 1964) from radar measurements in the Solar System. Signals from A are measured after they have passed through the distorted space-time of B (in principle the effect could also be measured for the signals from B but its pulses are much broader and do not provide sufficient temporal resolution). The signal delay is essentially a function of two parameters: $s$, the shape, and $r$, the range, of the delay experienced by the pulses (with $s$ being dependent on the inclination of the orbital plane and $r$ on the mass of B).

**Gravitational radiation and orbital decay,** $\mathrm{dP_b/dt}$**.** Almost every theory of gravitation predicts that the movement of massive bodies around one another in a binary system will result in the emission of gravitational waves. This emission causes the bodies to lose energy and hence to spiral into one another, so that they will eventually merge, creating a burst of gravitational waves when they do so. The rate of decrease of the orbital period, $\mathrm{dP_b/dt}$, indicates that orbits of the pulsars are currently shrinking by about 7 mm per day.

These effects can be used to carry out the elegant tests of general relativity described by Thibault Damour and Joe Taylor in 1992. They showed (Damour & Taylor 1992) that in any reasonable theory of gravity each PK parameter can be written as a function of the masses of the neutron stars, which are not known, and the Keplerian orbital parameters, which can all be measured with high precision. In other words, for each PK parameter there is a unique relationship between the two masses of the system. Thus, by inserting the measured value of each PK parameter into the associated equation linking the two masses, one can plot the allowed masses of A and B as a curve in a plot of one mass against the other (see Figure 1). For a theory of gravity to be correct, all the curves have to meet at a single point representing the actual values for the masses of the pulsars.

To date, some such tests have been carried out in two double-neutron-star systems: in PSR B1913+16 (Taylor & Weisberg 1989) and in PSR B1534+12 (Stairs et al. 2002). However, in the double-pulsar system we gain an additional parameter because both pulsars are visible and we can measure the sizes of orbits of

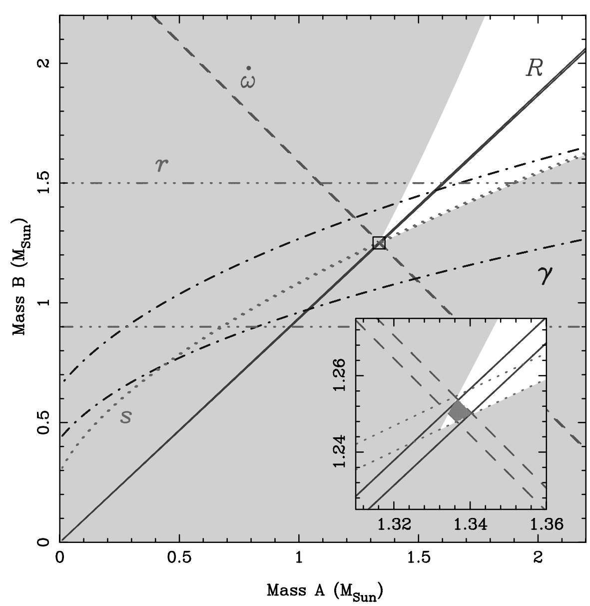


**Fig. 1** The mass-mass diagram for the J0737−3039 system. Each measurement of a post-Keplerian parameter or the mass ratio places restrictions on the two stellar masses in the system. On this diagram, the allowed areas are represented by regions lying between pairs of lines. All the measurements so far are consistent with a small allowed region near the centre of the small square frame which has been expanded in the inset diagram by a factor of about 16.

both objects with high precision. This gives us uniquely the ratio of the two stellar masses through

$$R = \frac{a_{\rm B}\ \sin i}{a_{\rm A}\ \sin i} = \frac{m_{\rm A}}{m_{\rm B}} = 1.069(6)\,. \tag{1}$$

This condition is independent of any theory of gravity and can be represented as a straight line passing through the origin in the mass-mass diagram. The intersection point of all the other curves must therefore lie on this line. As Figure 1 shows, the measurements carried out so far on PSR J0737−3039 are fully consistent with general relativity, further demonstrating Einstein's remarkable insight.

We are also able to obtain the masses of the neutron stars with very high precision. Our calculations after only six months of observation gave $1.337\pm0.005$ solar masses for A and $1.250\pm0.005$ solar masses for B, which is the lightest neutron star ever discovered (Lyne et al. 2004). Plugging these values back into the parameter functions then allows us to estimate the expected value of each PK parameter and to compare it with that observed. For instance, the ratio of the values of the Shapiro parameter, s, predicted by general relativity and that observed is $1.001\pm0.002$. We note that the errors in the measurements of all the post-Keplerian parameters will continue to decrease with the time-span of the observations to the power of between $-0.5$ and $-2.5$.

A further post-Keplerian effect is likely to be observed within a few years, that of geodetic precession, which arises because of the general-relativistic spin-orbit coupling within the system. The pulse-shape changes expected from this have already been observed in the B1913+16 system (Weisberg & Taylor 2002; Kramer 1998), in which the precession period is about 300 years. In the cases of the two pulsars in the J0737−3039 system, the precessional periods are about a factor of four smaller (Lyne et al. 2004). However, so far no changes attributable to precession have been observed for A, suggesting that the rotation and orbital angular momentum vectors are aligned and that the last supernova explosion produced very little "kick" that might have misaligned them (Manchester et al. 2005).

The measured value of s also shows that the orbit of the PSR J0737−3039 system is within 2 degrees of being edge-on as seen from Earth. This result was confirmed by interstellar scintillation measurements using the Green Bank Telescope in West Virginia (Ransom et al. 2004), although the results needed to be modified to account for anisotropy in the scattering medium (Coles et al. 2005).

## 3 THE COALESCENCE RATE OF DOUBLE NEUTRON STARS

The rate of decrease of the orbital period, $\mathrm{dP_b/dt}$, indicates that orbits of the pulsars are shrinking by about 7 mm per day, suggesting that A and B will merge in about 85 million years (Burgay et al. 2003). Combined with the knowledge that the system is relatively near to the Sun and that it has a low radio luminosity, this rather short timescale suggests that the current generation of gravitational-wave observatories such as LIGO may detect bursts of gravitational waves from such colliding neutron stars as often as once every few years (Kim, Kalogera & Lorimer 2003; Kalogera et al. 2004).

## 4 PROBING THE PLASMA

The double pulsar provides an unprecedented opportunity to study the workings of pulsars and their magnetospheres - the regions of space around pulsars in which the radio emissions are generally created. In fact, the emission from both pulsars is observed at some times to bear the rotational imprint of the other.

Firstly, the emission from B varies systematically as it traces out its orbit (Figure 2), both in intensity and in pulse shape, probably because a wind of charged particles and powerful electromagnetic radiation emerging from A blows away about half of the magnetosphere of its partner, resulting in an asymmetrical emission of radio waves (Lyne et al. 2004). In understanding what is happening, it is important to appreciate that, as seen in Table 1, the rate of loss of rotational energy by A is about 4,000 times that lost by B, and this will be reflected in a similar difference in their emission of energy in the form of relativistic particles and electromagnetic radiation. The dominant role of A over B is further revealed by a careful examination of Figure 2, presented by Maura McLaughlin at Jodrell Bank and colleagues (McLaughlin et al. 2004a). This reveals a modulation at 22.7 milliseconds in the pulses of B, seen as slightly downward-sloping drifts within the pulse. This shows directly the influence of A on B and probably arises from the impact of electromagnetic radiation emitted by A with the frequency of 44 Hz impacting upon the magnetosphere of B. In fact the sloping drifts can be modelled exactly by assuming that the 44 Hz radiation travels between

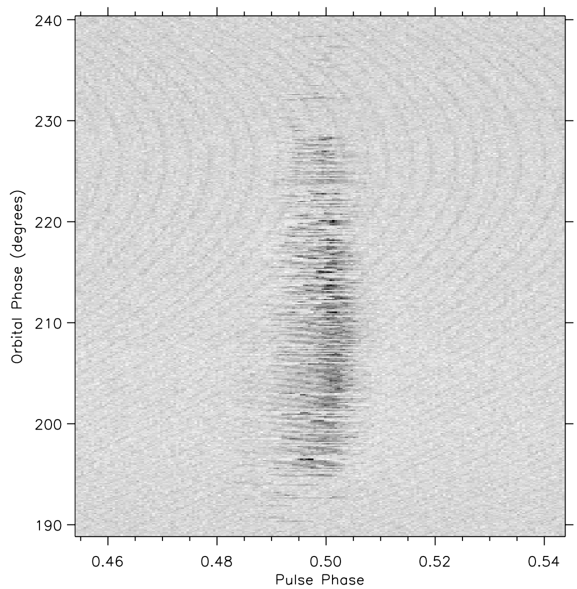


**Fig. 2** Data from the J0737−3039 system strobed at the 2.77-second observed rotation rate of B. This shows part of the orbit containing one of the two 10-minute longitude ranges where it is bright, and the pulses can be seen running down the middle of the diagram. Only 10% of the period of B around the pulse is shown. Single pulses from A can also be seen following approximately parabolic tracks. Differential Doppler effects result in the observed pulsation periods varying and they differ by exactly a factor of exactly 122 at orbital phase 226° where the tracks from the two pulsars are parallel. Careful study of the wide pulses of B reveal fine structure seen as slightly downward-sloping features representing modulation of its emission at the 22.7-ms rotation period of A.

the two pulsars at exactly the velocity of light. The pattern repeats every orbit but has been found to evolve in time (Burgay et al. 2005).

Zhang & Loeb (2004) and Lyutikov (2005) have proposed models in which the variations are due to the changing direction of impact of the A wind on the B magnetosphere. Zhang & Loeb propose that the B pulse emission is enhanced by the A wind penetrating deep into the B magnetosphere and directly emitting curvature radiation, whereas Lyutikov suggests that the A wind simply modulates the B pulse beam direction, moving it in and out of our line of sight at different orbital phases.

Secondly, much of the emission from A disappears for about 30 s in each orbit (Figure 3). This occurs when A passes behind B, so it is clear that the signal from A is being absorbed by the relativistic plasma surrounding its partner (Lyne et al. 2004; McLaughlin et al. 2004b). This eclipsing of A is possible because the orbits of the binary system happen to be almost exactly edge-on as seen from Earth (section 2), and means that we can probe the structure and density of the magnetosphere of B using the A signal. During this time, high time resolution measurements show the imprint of the rotating magnetosphere of B in the pulses of A as they pass through it (McLaughlin et al. 2004b). This is the first time such a feat has been possible. Indeed, it is clear that the degree of absorption depends on the orientation of B's magnetic poles as it passes in front of A, allowing measurement of the transparency of B's magnetosphere as a function of the pulsar's orientation (Figure 3). The eclipse is probably due to synchrotron absorption, either within a magnetosheath surrounding B's magnetosphere (Lyutikov 2004; Arons et al. 2005) or within the closed-field-line region of the magnetosphere (Rafikov & Goldreich 2005; Lyutikov & Thompson 2005).

## 5 CONCLUSIONS

Several fortunate circumstances have come together to make these studies possible. Not only is this a double-neutron-star system, but

- It has a very compact orbit, giving rise to intense gravitational fields and accelerations and hence abundant post-Keplerian gravitational effects
- One pulsar is a millisecond pulsar which enables these effects to be measured with high precision
- Both neutron stars are visible, allowing the mass-ratio to be determined
- Both pulsars have large flux densities, giving high-precision measurements
- The orbit is nearly edge on, so that the Shapiro delay can be measured with high precision.

All these properties enhance the quality and speed of the tests of gravitation theories in the strong-field regime. Furthermore, the last three also enable the investigations of the interactions between the stars and the probing of the magnetospheric properties.

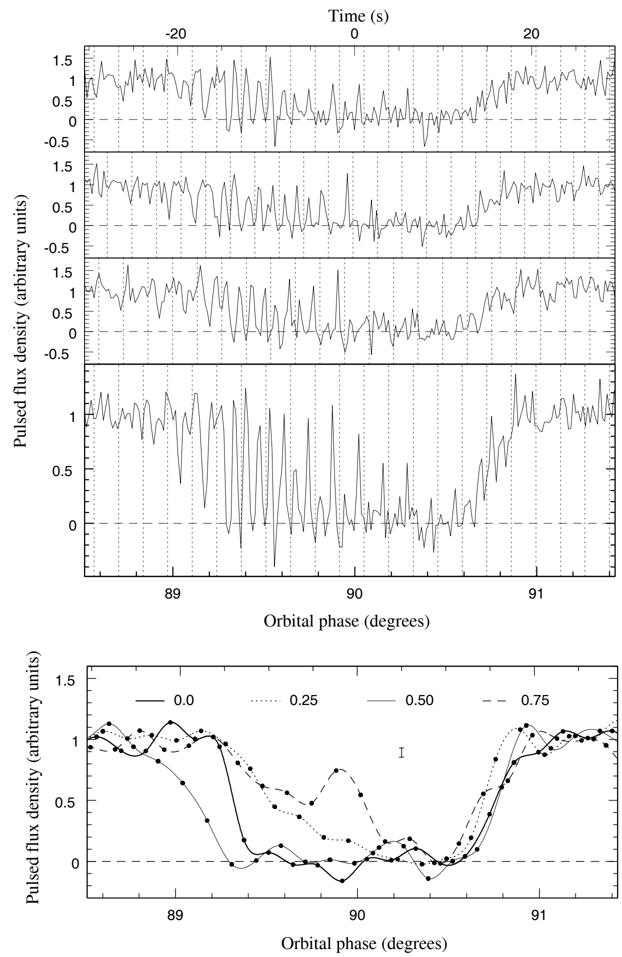


**Fig. 3** Approximately 70 seconds of data showing the eclipse of A by the magnetosphere of B, showing the modulation of the radiation by the rotation of the magnetosphere of B. The top three traces show high time resolution plots of three consecutive eclipses. The vertical dotted lines represent the times when the radio pulses of B arrive at the Earth and its active magnetic pole is directed at us. The fine features in the eclipses are clearly synchronised with this rotation. The diagram just below is the average eclipse profile obtained by summing the eclipses after a small adjustment to align them with the rotation of B. The bottom diagram is the form of the eclipse for each of four different rotation phases of B. The eclipse is clearly deepest and longest at phase 0.5, i.e. when the non-radiating magnetic pole is directed towards the Earth (McLaughlin et al. 2004b).

Future observations of binary systems like PSR J0737−3039 promise to greatly increase our knowledge of strong-field gravity, but finding these systems will be a challenge. This is because double pulsars are extremely rare and, more importantly, because the Doppler effect causes their pulse periods to vary rapidly even during a short observation. It therefore becomes more difficult to detect the pulsars' periodicity using normal Fourier techniques and more sophisticated and computationally challenging search algorithms will have to be employed to uncover them.

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