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The Double Pulsar System J0737-3039

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Abstract. The double pulsar system J0737−3039A/B is one of the most intriguing pulsar discoveries of the last decade. This binary system, with an orbital period of only 2.4-hr, provides a truly unique laboratory for relativistic gravity. Its discovery enhances of about an order of magnitude the estimate of the merger rate of double neutron stars systems, opening new possibilities for the current generation of gravitational wave detectors. The high orbital inclination, moreover, offers the opportunity to use the radio beams from one pulsar as a probe for studying the magnetosphere of the other. In this contribution we summarize the present results and look at the prospects of future observations.

Key words. Neutron star – Pulsar: individual (PSR J0737-3039A/B) – General Relativity

1. Introduction

The 22.7-ms pulsar PSR J0737-3039A (hereafter 'A') was discovered by our team in April 2003 (Burgay et al. 2003) in the Parkes High-Latitude Pulsar Survey (Burgay et al. 2005b,in preparation). Its short spin period (P_b = 2.4 hrs), combined with a remarkably high value of the periastron advance ($\dot{\omega}$ = 16.9 deg/yr), measurable after only few days of observations, identified it soon as a member of the most extreme relativistic binary system ever discovered. The compactnes of the system, together with its short coalescence time (T_{coal} = 85 Myr) and low luminosity, boosts hopes to detect mergers of neutron stars with ground based

Send offprint requests to: Marta Burgay gravitational wave detectors, increasing the estimates on the double neutron star colaescence rate by almost an order of agnitude (Burgay et al. 2003; Kalogera et al. 2004).

Analysis of follow-up observations, covering the entire orbit, led, in October 2003, to the discovery of the second pulsar in the system (Lyne et al. 2004), the 2.8-s pulsar J0737-3039B (hereafter 'B'). The reason why the signal of pulsar A's companion was not detected earlier is that B is only brigth in two short sections of the orbit; for the rest of the orbit the signal is very week or absent.

A closer inspection to the signals of both pulsar A and B reveals also other intriguing characteristics: pulsar A is eclipsed for $\sim$ 30 s near superior conjunction, with the shape and depth of the eclipsed region influenced by pulsar B (McLaughlin et al. 2004b), and pulsar B shows variations in the pulse shape along the orbit (Lyne et al. 2004) and a drifting signature in its single pulses, in phase with the pulsations of A as received at B's surface (McLaughlin et al. 2004a). More recently, also variations of the extent and location of B's bright phases and of the pulse shape on longer time scales, have been observed (Burgay et al. 2005a). These phenomena are probably related to the geodetic precession of pulsar A and B (estimated to have a period of only 75 and 71 yr respectively) that are changing the geometry of the system and hence our view towards it.

In this contributions, we will concentrate on the description of the binary system J0737-3039A/B as test-ground for relativistic theories (§2) and on the possibilities opened by the presence of two interacting pulsars to study pulsars' magnetospheres and emission mechanisms (§3)

2. Test of General Relativity

Due to their strong gravitational fields and rapid motions, the binary systems containing two neutron stars exhibit large relativistic effects (Damour & Deruelle 1986). When these are large enough, the system can be used for testing the predictions of theories of gravity in the strong-field limit. Tests can be performed when a number of relativistic corrections to the Keplerian description of an orbit, the so called, "post-Keplerian" (PK) parameters, can be measured. In each theory the PK parameters can be written as a function of the masses of the two stars and of the measurables Keplerian parameters. With the two masses as the only unknowns, the measurement of three or more PK parameters over-constrains the system hence providing tests for a given theory of gravity (Damour & Taylor 1992).

In General Relativity (GR) the post-Keplerian parameters can be written (at first post-Newtonian order, 1PN) as follows (Damour & Deruelle 1986):

$$
\begin{aligned}
\dot{\omega} &= 3T_{\odot}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\,(M_A+M_B)^{2/3},\\
\gamma &= T_{\odot}^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{M_B(M_A+2M_B)}{(M_A+M_B)^{4/3}},\\
\dot{P}_b &= -\frac{192\pi}{5}T_{\odot}^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)}{(1-e^2)^{7/2}}\frac{M_A M_B}{(M_A+M_B)^{1/3}},\\
r &= T_{\odot}M_B,\\
s &= T_{\odot}^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3} x\,\frac{(M_A+M_B)^{2/3}}{M_B},
\end{aligned}
$$

where P_b is the orbital period, e the eccentricity and x the projected semi-major axis of the orbit measured in light-s. The masses M_A and M_B of A and B respectively (or, in general, of the pulsar and its companion), are expressed in solar masses ($M_{\odot}$). We define the constant $T_{\odot} = GM_{\odot}/c^3 = 4.925490947\mu$s where G denotes the Newtonian constant of gravity and c the speed of light. The first PK parameter, $\dot{\omega}$ describes the relativistic advance of periastron. The parameter γ denotes the amplitude of delays in arrival times caused by the varying effects of the gravitational redshift and time dilation as the pulsar moves in its elliptical orbit at varying distances from the companion and with varying speeds. The decay of the orbit due to gravitational wave damping is expressed by the change in orbital period, $\dot{P}_b$. The other two parameters, r and s, are related to the Shapiro delay caused by the gravitational field of the companion.

The PK parameter can be plotted on a mass-mas diagram (see e.g. Fig. 1) and, if the

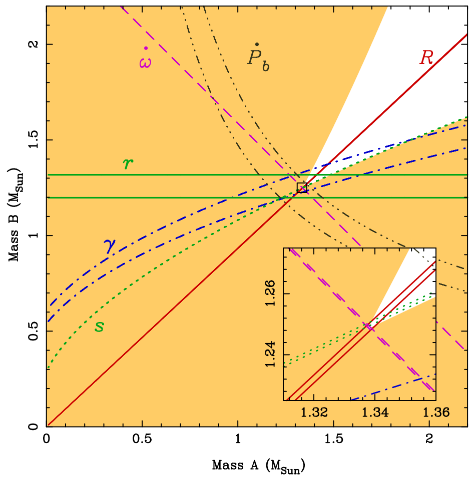

Fig. 1. The observational constraints upon the masses M_A and M_B. The colored regions are those which are excluded by the Keplerian mass functions of the two pulsars. Further constraints are shown as pairs of lines enclosing permitted regions as predicted by general relativity: (a) the measurement of the advance of periastron $\dot{\omega}$ (dashed lines); (b) the measurement of the mass ratio R (solid lines); (c) the measurement of the gravitational red-shift/time dilation parameter γ (dot-dash lines); (d) the measurement of Shapiro parameter r (solid horizontal lines) and Shapiro parameter s (dotted lines); (e) the measurement of the orbital decay (dot-dot-dot-dash lines). Inset is an enlarged view of the small square which encompasses the intersection of the three tightest constraints, with the scales increased by a factor of 16. The permitted regions are those between the pairs of parallel lines and we see that an area exists which is compatible with all constraints.

theory tested is correct, the curves on the plane must intersect in a single point.

In this context, PSR J0737-3039A/B promises to be the most powerfull instrument to test GR (and other theories) providing us with *two* pulsars, extremely stable clocks, in the same system. Timing measurements of pulsar A, infact, have already provided all 5 post-Keplerian parameters with high accuracy (see Table 1). Moreover, with the knowledge of the projected semimajor-axes for both A and B, we obtain a precise measurement of the mass ratio R of the two stars:

$$R \equiv M_A/M_B = x_B/x_A \qquad (1)$$

For every realistic theory of gravity, we can expect the mass ratio, R, to follow this simple relation (Damour & Taylor 1992), at least to 1PN order. Most importantly, the R value is not only theory-independent, but also independent of strong-field (self-field) effects which is not the case for PK-parameters. This provides a stringent and new constraint for tests of gravitational theories as any combination of masses derived from the PK-parameters *must* be consistent with the mass ratio. With five PK parameters already available, this additional constraint makes the double pulsar the most overdetermined system to date providing four possible tests for relativistic theories.

Since the precision with which we can measure the PK parameters increases with time, continued observation of J0737-3039A/B will eventually provide us with the necessity to include higer order corrections to the PK parameters. In particular, within few years, we could be able to measure the contribution of the spin-orbit coupling to the observed $\dot{\omega}$. This extra term in the periastron advance is related to the moment of inertia of the star which would be measured for the first time for a neutron star also providing tight constraints on the neutron stars' equation of state.

3. Probing Pulsar's Magnetospheres

Figures 2 and 3 show a series of integrated pulses of A and B respectively, as a function of the orbital phase. As pointed by the arow in Fig. 2 , A experiences a short eclipse ($\sim$ 30 s) at superior conjunction. B's behaviour is even more puzzling: as shown in Fig. 3 its pulses are strong only in two short orbital phases, around orbital longitudes (with respect to the ascending node) $\sim 210°$ and $\sim 280°$, becoming fainter or undetectable at other phases.

All these features call for some sort of interaction between the two pulsars. Many interpretation of these phenomena has been

Pulsar	PSR J0737−3039A	PSR J0737−3039B
Pulse period P (ms)	22.699378556138(2)	2773.4607474(4)
Period derivative $\dot{P}$	$1.7596(2) \times 10^{-18}$	$0.88(13) \times 10^{-15}$
Epoch of period (MJD)	52870.0	
Right ascension α (J2000)	$07^{h}37^{m}51^{s}.24795(2)$	
Declination δ (J2000)	$-30°39'40''.7247(6)$	
Orbital period P_{b} (day)	0.1022515628(2)	
Eccentricity e	0.087778(2)	
Epoch of periastron T_0 (MJD)	52870.0120588(3)	
Advance of periastron $\dot{\omega}$ (deg yr^{-1})	16.900(2)	
Longitude of periastron ω (deg)	73.805(1)	73.805 + 180.0
Projected semi-major axis $x = a\sin i/c$ (sec)	1.415032(2)	1.513(4)
Gravitational redshift parameter γ (ms)	0.39(2)	
Shapiro delay parameter $s = \sin i$	0.9995(4)	
Shapiro delay parameter r (μs)	6.2(6)	
Orbital decay $\dot{P}_b$ (10^{-12})	−1.20(8)	
Mass ratio $R = M_A/M_B$	1.071(1)	

Table 1. Observed and derived parameters of PSRs J0737−3039A and B. Number in parentheses are standard errors on the last digit(s).

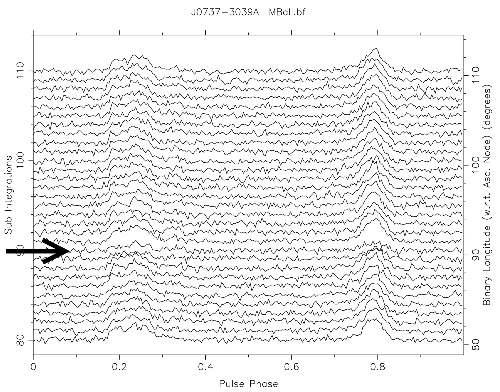

Fig. 2. A series of subsequent integrated pulse profiles of PSR J0737-3039A plotted versus the orbital longitude in the longitude range 80° – 110°. At longitude ∼ 90° a short eclipse is present in the signal.

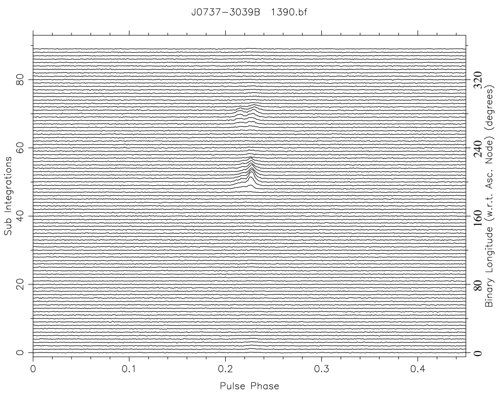

Fig. 3. A series of subsequent integrated pulse profiles of PSR J0737-3039B plotted versus the orbital longitude over an entire orbit (only the pulse phase range 0.0 – 0.45 is plotted). The signal is strong only around longitudes 210° and 280°.

given by different authors (see e.g. Lyutikov 2004; Arons et al. 2004; Zhang & Loeb 2004; Lyutikov & Thompson 2005; Lyutikov 2005,for details).

Observationally, the hipothesis of a mutual influence of one pulsar on the other has been found analysing in more details the single pulses of PSR B and PSR A eclipse. Figure 4 (left panel) shows the single pulses of J0737-3039B in the orbital longitudes 200° – 210°: a drifting signature can be seen and, overlapping to the figure the times of arrival of the pulses

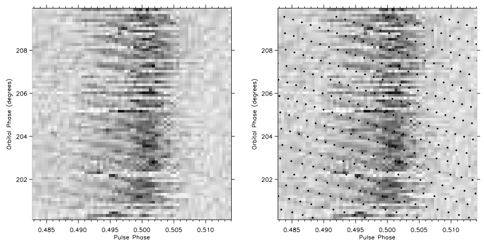

Fig. 4. Left: single pulses of B at 820 MHz for orbital longitudes 200° – 210° on MJD 52997. Only 10% of the pulse period of B is shown. Drifting features are present through these data. Right: dots denote the arrival at the centre of B of emission from an arbitrary rotational phase of A, retarded by the propagation time across the orbit.

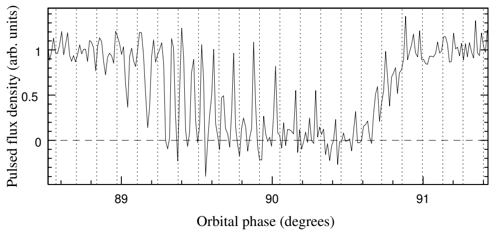

Fig. 5. Light curves for A's eclipse @ 820 MHz. The vertical dashed lines indicate the measured arrival times of the pulses of B.

of J0737-3039A *at B's surface* (dots in Fig. 4, right panel), we can immediately see that the two patterns overlap perfectly indicating that the signatures in B's pulses are due to the influence of A's 44 Hz radiation.

Figure 5 shows the pulsed flux density of A versus orbital longitude (wrt ascending node) at 820 MHz with a time resolution of 0.27 s. On this plot, we also indicate (vertical lines) the measured barycentric arrival times of the pulses of the 2.8 s pulsar B. The coincidence of these lines with the fluctuations observed at the ingress of A eclipse demonstrates clearly that the pulsed flux density of A is modulated in synchronism with half the B spin period. This, along with the fact that the eclipses are longer and deeper at those rotational phases (phases 0.0 and 0.5 in Fig. 6) at which B's beam is facing pulsar A, supports the idea first proposed

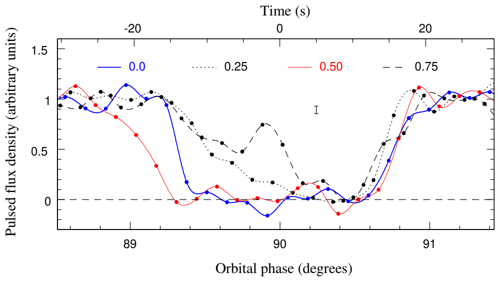

Fig. 6. Averaged light curves for four regions of B pulse phase. The four regions are centered on pulse phases 0.0, 0.25, 0.50 and 0.75, with, for example, the curve for 0.0 covering the 0.25 of pulse phase centered on B's radio pulse.

by Arons et al. (2004) that A's signal is absorbed by a magnetosheat surrounding B pulsar, created by the shock front due to the interaction between the energetic A's wind and B' magnetosphere. This magnetosheat is thicker near B's polar caps hence producing a wider and sharper eclipse at the rotational phases at which B's radio beams are pointing towards A. In summary, detailed studies on the emission features of PSR A and B are for the first time providing unique tools to inspect the interaction between the two pulsars and to study pulsars' magnetospheres and emission mechanisms using the beam of one pulsar as a probe for the other.

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