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The double-pulsar PSR J0737−3039A/B

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Abstract. The double-pulsar system J0737-3039 is one of the most promising targets for a variety of astrophysical investigations. Its orbital parameters enable unique tests of the theories of Gravity and make the system an unprecedented laboratory for the physics of highly condensed matter. The high orbital inclination opens the possibility of using the radio beams from the two sources as a probe for investigating the so far unaccessible magnetosphere of a pulsar. The discovery of this system also increases of about an order of magnitude the estimates of the merger rate of double neutron stars systems, opening new opportunities for the current generation of gravitational wave detectors.

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

1. The discovery

Since the discovery of the first binary pulsar (Hulse & Taylor 1975), the detection of two active pulsars in the same binary system has been an ambition of any pulsar survey. PSR J0737−3039A, a millisecond pulsar with a spin period of 22.7 ms, was discovered in April 2003 (Burgay et al. 2003) in a 4-minute pointing of the Parkes High-Latitude Pulsar Survey (Burgay et al. in preparation). Despite the short duration of the observation, the pulsar signal displayed a significant Doppler effect, suggestive of a gravitational pull on the pulsar due to a nearby and relatively massive companion. Follow-up observations performed in May

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2004 confirmed that the orbit is indeed very tight and elliptical: the binary period P_b is only 2.4 hr and the eccentricity e about 0.09. This makes J0737−3039A's orbit the tightest among those of all known binary pulsars in eccentric systems. The pulsar mass function was calculated and resulted 0.29 $M_\odot$.

A strong constraint on the nature of PSR J0737−3039A companion came few days later from the first fit of a binary model to the times of arrival of the pulsations. By using a data span of only 6 days, a 10-σ determination of the advance of the periastron, $\dot{\omega}$, was possible. This parameter resulted to have a remarkably high value: $\dot{\omega} \sim 17^o$/yr. Note that the the previously highest observed value was 5.33^o/yr for PSR J1141-6545, (Kaspi et al. 2000). If interpreted in the framework of general relativity, the measured value of $\dot{\omega}$ implied a total mass for the system containing PSR J0737−3039A of about 2.58 $M_\odot$ giving a maximum mass for the pulsar of about 1.34 $M_\odot$ and a minimum mass for the companion of 1.24 $M_\odot$. The maximum mass for the pulsar perfectly agrees with the other measurements of neutron star masses (Thorsett & Chakrabarthy 1999), while the mass of the companion is only slightly lower than average. This piece of evidence strongly suggested that the discovered binary was a new, and by far the most relativistic, Double Neutron Star (DNS) system.

The ultimate confirmation of the above picture came few months later when, analysing the follow-up observations of PSR J0737−3039A, a strong signal with a repetition period of about 2.8 seconds occasionally appeared (Lyne et al. 2004). The newly discovered pulsar, henceforth called PSR J0737−3039B (or simply B), had the same dispersion measure as PSR J0737−3039A (or A), and showed orbital Doppler variations that identified it, without any doubt, as the companion to the millisecond pulsar. The first ever Double Pulsar system had been eventually discovered.

2. A unique test-bed for Relativistic Gravity

Due to their strong gravitational fields and rapid motions, the double neutron star binaries exhibit large relativistic effects. PSR J0737−3039A/B promises to ensure the best tests of General relativity and other theories of gravity than ever before. Tests can be performed when a number of relativistic corrections to the Keplerian description of the orbit (the so-called post-Keplerian, hereafter PK, parameters) can be measured. In this formalism, for point masses with negligible spin contributions, the PK parameters in each theory should only be functions of the a priori unknown neutron star masses and the classical Keplerian parameters. With the two masses as the only free parameters, the measurement of three or more PK parameters over-constrains the system, and thereby provides a test-ground for theories of gravity (Damour & Taylor 1992). In a theory that describes the binary system correctly, the PK parameters define lines in a mass-mass diagram that all intersect in a single point. Such tests have been possible to date in only two double neutron star systems, PSR B1913+16 (Taylor & Weisberg 1989) and PSR B1534+12 (Stairs et al. 2002). For PSR B1913+16, the relativistic periastron advance, $\dot{\omega}$, the orbital decay due to gravitational wave damping, $\dot{P}_b$, and the gravitational redshift/time dilation parameter, γ, have been measured, providing a total of three PK parameters. For PSR B1534+12, Shapiro delay, caused by passage of the pulses through the gravitational potential of the companion, is also visible, since the orbit is seen nearly edge-on. This results in two further PK parameters, r (range) and s (shape) of the Shapiro delay. However, the observed value of $\dot{P}_b$ requires correction for kinematic effects, so that PSR B1534+12 provides four PK parameters usable for precise tests (Stairs et al. 2002). With a intense campaign of regular timing observations started immediately after the discovery, we have measured A's $\dot{\omega}$ and γ and have also detected the Shapiro delay in the pulse arrival times of A due to the gravitational field of B. This provides four measured PK parameters, resulting in a M_A-M_B plot (Fig. 1) through which we can test the predictions of general relativity. In particular the current data, spanning only 10 months of observations, indicate an agreement of the observed with the

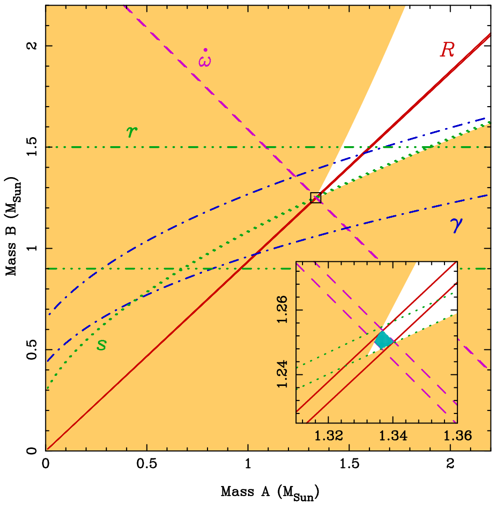

Fig. 1. The observational constraints upon the masses M_A and M_B. The colored regions are those which are excluded by the Keplerian mass functions of the two pulsars. Further constraints are shown as pairs of lines enclosing permitted regions as predicted by general relativity: (a) the measurement of the advance of periastron $\dot{\omega}$, giving the total mass $M_A+M_B=2.588\pm0.003$ $M_\odot$ (dashed line); (b) the measurement of R= $M_A/M_B = x_B/x_A = 1.069\pm0.006$ (solid line); (c) the measurement of the gravitational redshift/time dilation parameter γ (dot-dash line); (d) the measurement of Shapiro parameter r giving $M_B = 1.2\pm0.3$ $M_\odot$ (dot-dot-dot-dash line) and (e) Shapiro parameter s (dotted line). 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, delineated by the solid blue region.

expected Shapiro parameter s of s_{obs}/s_{exp}= 1.00007±0.00220 where the uncertainties are likely to decrease quickly.

However, the detection of B as a pulsar opens up opportunities to go beyond what is possible with previously known double neutron star binary systems. Firstly, we can exclude all regions in the M_A-M_B plot plane that are forbidden by the individual mass functions of A and B due to the requirement $\sin i \leq 1$ (where i is the inclination of the orbital plane). Secondly, with a measurement of the projected semi-major axes of the orbits of A and B, we obtain a precise measurement of the mass ratio, $R(M_A, M_B) = M_A/M_B = x_B/x_A$, providing a further constraint in the M_A-M_B plot (Fig. 1). This relation is valid for any theory of gravity; most importantly, the R-line is independent of strong-field (self-field) effects, providing a new constraint for tests of gravitational theories (Damour & Deruelle 1986). With four PK parameters already available for tests, this additional constraint makes this system the most over-determined double neutron star binary. Moreover, with a significant measurement of $\dot{P}_b$ expected within the next few months, an additional PK parameter will become available. This may provide a sixth constraint if kinematic effects are negligible or can be isolated by proper motion and distance measurements. The position of the allowed region in Fig. 1 also determines the inclination of the orbit to the line-of-sight. It turns out that the system is observed nearly edge-on with an inclination angle of about 87^o.

Due to the curvature of space-time near massive objects, the spin axes of both pulsars will precess about the total angular momentum vector, changing the orientation of the pulsars as seen from Earth (Damour & Ruffini 1974). General relativity predicts periods of such geodetic precession of only 75 yr for A and 71 yr for B. This should lead to measurable changes in the profiles of A and B. Deviations from the value predicted for $\dot{\omega}$ by general relativity may be caused by contributions from spin-orbit coupling (Barker & O'Connell 1975), which is about an order of magnitude larger than for PSR B1913+16. This potentially will allow us to measure the moment of inertia of a neutron star for the first time and in turn to constrain the equation of state for the nuclear matter.

3. A magnificent laboratory for Plasma Physics

3.1. The Orbital modulation of B

PSR B was not detected in the original discovery observation: this is because pulses from the B pulsar are only strong for two short intervals each orbit. The discovery observation happened to be at a time when B pulsed emission is very faint. The first burst of strong emission, centered near orbital longitude 210^o (calculated from the ascending node) covers about 40^o of longitude (about 13 min) and the second, centered near longitude 280^o, covers about 25^o of longitude (about 8 min). There is no discernable variation of the modulation pattern from orbit to orbit and the orbital modulation of the pulse intensity is broadly independent of frequency, at least over the observed range, from 680 MHz up to 3030 MHz.

The energy density at the B pulsar of the wind resulting from spin-down of the A pulsar is about 2.1 erg cm−3. This is about two orders of magnitude greater than the energy density (or equivalently, pressure) of the B pulsar wind at its light cylinder radius R_{LC}. Hence, the A wind will penetrate deep into the B-pulsar magnetosphere. The penetration depth is determined by pressure balance between the A wind and the B dipolar magnetic field giving an effective Alfven radius of about 0.45 R_{LC}. This implies that 90 percent of the B-pulsar magnetosphere is blown away by the A wind! There can be little doubt that the observed orbital modulations of the B pulse shape and intensity are due to interactions of the A wind with the emission process. The fact that B is able to function as a pulsar at all implies that the emission is located well within the nominal light cylinder. The site of the radioemission in radiopulsar (inner magnetosphere or regions close to the light cylinder) is a fundamental, but still unanswered question. The investigation of the radiosignals from B could give important clues for discriminating between the two scenarios.

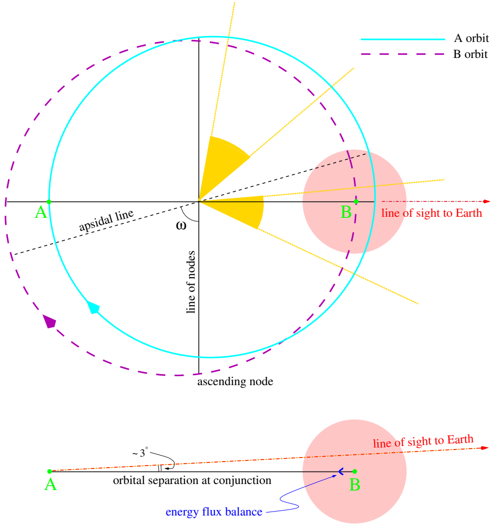

Fig. 2. Geometry of the PSR J0737−3039A/B system and regions of pulsed emissions at 20cm. The B pulsar displays a strong pulsed flux at the two orbital phases indicated by yellow shaded slices. The pulsation is also detectable, at a much weaker level, at other orbital phases. The A pulsar is visible along the entire orbit, except for a ∼ 30-sec eclipse occurring at the superior conjunction.

3.2. The Eclipse of A

At superior conjunction (90^o orbital longitude) pulsar A experiencies a very short eclipse with a duration of less than 30 sec orresponding to a width of the eclipsing region at the B pulsar position of about 18,000 km or about 0.14 R_{LC}. Observations at the 50 cm and 10 cm bands show that within the uncertainties the eclipse duration is independent of frequency. The best estimate or the orbital inclination ($87^o.7$) corresponds to an impact parameter of about 35,400 km or 0.26 R_{LC} at the B pulsar, much greater than the width of the eclipsing region (see Fig. 2).

3.3. Unpulsed emission

There is some evidence for significant unpulsed emission from the J0737−3039 system. The mean pulsed flux density of A at 20 cm is about 1.6 mJy (Lyne et al. 2004). During the first burst, B's 20-cm flux density is similar, but its duty cycle is only about 15 percent so it makes a small contribution to the long-term mean. In contrast, a 6-hour synthesis image using the Australia Telescope Compact Array (Burgay et al. 2003) gave a mean flux density of about 6 mJy at 20 cm. Taken at face value, it implies substantial unpulsed emission from the system, never detected before in binary pulsars. The spectrum and origin of this unpulsed emission are presently unknown.

3.4. Challenges for the future

Clearly this unique A's wind vs B's magnetosphere "collider" may give us the possibility of unveiling many so far unaccessible features of the physics of a pulsar magnetosphere and of the pulsar emission mechanism itself, such as the degree of magnetization and the isotropy of the wind (Kennel & Coroniti 1984), the energetic distribution (among accelerated particles, γ-rays and electromagnetic radiation at the pulsar spin frequency) of the pulsar flux, the validity of the usual dipole relation for calculating the magnetic field strength in B, the plasma density in the closed magnetosphere or the already mentioned height over the neutron star surface of the region responsible for the radio emission. The first attempts of modeling the various phenomenologies (Lyutikov 2004)(Arons et al. 2004) invoke synchrotron absorption in a shock-heated "magnetosheath" surrounding the B pulsar or the illumination of the A's wind onto B's magnetosphere, which could trigger bursts of coherent radioemission from the latter (Jenet & Ransom 2004).

4. Improved perspectives for detection of gravitational waves

Among the double-neutron-star systems known so far, only three have tight enough orbits so 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 (Phinney 1991). Also, recent studies (Kalogera et al. 2004) have demonstrated that the current estimate of the Galactic merger rate $\mathcal{R}$ relies mostly on PSR B1913+16. So one can start by comparing the observed properties of PSR B1913+16 and PSR J0737−3039. The latter will merge due to the emission of gravitational waves in $\sim$ 85 Myr, a timescale that is a factor 3.5 shorter than that for PSR B1913+16. In addition, the estimated distance of PSR J0737−3039A/B (500 - 600 pc, based on the observed dispersion measure and a model for the distribution of ionised gas in the interstellar medium: Taylor & Cordes 1993) 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 $\mathcal{R}_k$ is calculated as $\mathcal{R}_k = N_k/\tau_k$ (Kalogera et al. 2004). Here τ_k is the binary pulsar lifetime 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 J0737−3039 system $[\tau_{1913}/\tau_{0737}$ = (365 Myr)/(185 Myr)] implies a doubling of the ratio $\mathcal{R}_{0737}/\mathcal{R}_{1913}$. A much more substantial increase results from the computation of the ratio of the scaling factors N_{0737}/N_{1913}. The luminosity L_{400}=30 mJy kpc^2 of PSR J0737−3039A is much lower than that of PSR B1913+16. For a planar homogeneous distribution of pulsars in the Galaxy, the ratio $N_{0737}/N_{1913} \sim L_{1913}/L_{0737} \sim 6$. Hence we obtain $\mathcal{R}_{0737}/\mathcal{R}_{1913} \sim 12$. Including the moderate contribution of the longer-lived PSR B1534+12 system to the total rate, we obtain an increase factor for the total merger rate of about an order of magnitude.

Extensive simulations (Kalogera et al. 2004) give results consistent with this simple estimate and show that the peak of the merger rate increase factor resulting from the discovery of J0737−3039 system lies in the range 6-7 and is largely independent of the adopted pulsar population model. For the most favourable distribution model available (model nr. 15 of Kim, Kalogera & Lorimer 2003), the updated cosmic detection rate for first generation gravitational-wave detectors such as VIRGO, LIGO and GEO can be as high as 1 every 1-2 years at 95% confidence level. Hence, with the discovery of PSR J0737−3039A/B the double-neutron-star coalescence rate estimates enter an astrophysical interesting regime. Within a few years of gravitational-wave detectors operations, it should be possible to directly test these predictions and, in turn, place better constraints on the cosmic population of double-neutron-star binaries.

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