The Double Pulsar System J0737–3039A/B as Testbed for Relativistic Gravity


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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. In this contribution we summarize the present results and look at the prospects of future observations.

1 Introduction

The 22.7-ms binary pulsar PSR J0737-3039A (hereafter ‘A’) was discovered in April 2003 [1] in the Parkes High-Latitude Pulsar Survey [2]. Its short orbital 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 compactness 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 gravitational wave detectors, increasing the estimates on the double neutron star coalescence rate by almost an order of magnitude [1, 3].

Analysis of follow-up observations, covering the entire orbit, led, in October 2003, to the discovery of the second pulsar in the system [4], 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 bright 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 and pulsar B shows variations in the pulse shape along the orbit [4]. Variations of the extent and location of
B’s bright phases and of the pulse shape on longer time scales have also been observed [5]. These phenomena are probably related to the geodetic precession of pulsar A and B 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 and on the implication of the discovery of this system on the probability to detect gravitational waves with ground based interferometers.

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 [6]. 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 [7].

In General Relativity (GR) the post-Keplerian parameters can be written (at first post-Newtonian order, 1PN) as follows [6]:

\[
\begin{align*}
\dot{\omega} &= 3T_{\odot}^{2/3} \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{1-e^2} (M_A + M_B)^{2/3}, \\
\gamma &= T_{\odot}^{2/3} \left( \frac{P_b}{2\pi} \right)^{1/3} \frac{e}{(M_A + M_B)^{4/3}}, \\
\dot{P}_b &= -\frac{192\pi}{5} T_{\odot}^{-5/3} \left( \frac{P_b}{2\pi} \right)^{-5/3} \frac{1}{(1-e^2)^{5/2}} (1 + \frac{74}{27} e^2 + \frac{37}{50} e^4) \frac{M_A M_B}{(M_A + M_B)^{1/3}}, \\
r &= T_{\odot} M_B, \\
s &= T_{\odot}^{-1/3} \left( \frac{P_b}{2\pi} \right)^{-2/3} x (M_A + M_B)^{2/3} M_B,
\end{align*}
\]

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. 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 \(\gamma\) 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 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 powerful instrument to test GR (and other theories) providing us with two pulsars, extremely stable clocks, in the same system. Timing measurements of pulsar A, in fact, have already provided all 5 post-Keplerian parameters with high accuracy (see Table 1). Moreover, with the knowledge of
Figure 1: The observational constraints upon the masses of the two pulsars in the system, $M_A$ and $M_B$. The coloured 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 $\gamma$ (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.
Table 1: Observed and derived parameters of PSRs J0737−3039A and B. Number in parentheses are standard errors on the last digit(s).

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>PSR J0737−3039A</th>
<th>PSR J0737−3039B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin frequency ω (Hz)</td>
<td>44.054069392744(2)</td>
<td>0.36056035506(1)</td>
</tr>
<tr>
<td>Spin frequency derivative ˙ω</td>
<td>−3.4156(1) × 10^{−15}</td>
<td>−0.116(1) × 10^{−15}</td>
</tr>
<tr>
<td>Epoch of period (MJD)</td>
<td>531560.0</td>
<td>531560.0</td>
</tr>
<tr>
<td>Right ascension α (J2000)</td>
<td>07h37m51s.24927(3)</td>
<td>07h37m51s.24927(3)</td>
</tr>
<tr>
<td>Declination δ (J2000)</td>
<td>−30°39′40″.7195(5)</td>
<td>−30°39′40″.7195(5)</td>
</tr>
<tr>
<td>Proper motion in the RA direction (mas yr^{−1})</td>
<td>3.3(4)</td>
<td>3.3(4)</td>
</tr>
<tr>
<td>Proper motion in Declination (mas yr^{−1})</td>
<td>2.6(5)</td>
<td>2.6(5)</td>
</tr>
<tr>
<td>Parallax (mas)</td>
<td>3(2)</td>
<td>3(2)</td>
</tr>
<tr>
<td>Orbital period P_b (day)</td>
<td>0.10225156428(5)</td>
<td>0.10225156428(5)</td>
</tr>
<tr>
<td>Eccentricity e</td>
<td>0.0877757(9)</td>
<td>0.0877757(9)</td>
</tr>
<tr>
<td>Epoch of periastron T_0 (MJD)</td>
<td>53155.9074280(2)</td>
<td>53155.9074280(2)</td>
</tr>
<tr>
<td>Advance of periastron ˙ω (deg yr^{−1})</td>
<td>16.89947(68)</td>
<td>16.89947(68)</td>
</tr>
<tr>
<td>Longitude of periastron ω (deg)</td>
<td>87.0331(8) + 180.0</td>
<td>87.0331(8) + 180.0</td>
</tr>
<tr>
<td>Projected semi-major axis x = asini/c (sec)</td>
<td>1.415032(1)</td>
<td>1.516(16)</td>
</tr>
<tr>
<td>Gravitational redshift parameter γ (ms)</td>
<td>0.3856(26)</td>
<td>0.3856(26)</td>
</tr>
<tr>
<td>Shapiro delay parameter s = sin i</td>
<td>0.99974(−39, +16)</td>
<td>0.99974(−39, +16)</td>
</tr>
<tr>
<td>Shapiro delay parameter r (µs)</td>
<td>6.21(33)</td>
<td>6.21(33)</td>
</tr>
<tr>
<td>Orbital decay ˙P_b</td>
<td>−1.252(17) × 10^{−12}</td>
<td>−1.252(17) × 10^{−12}</td>
</tr>
</tbody>
</table>

The double Pulsar J0737−3039A/B

For every realistic theory of gravity, we can expect the mass ratio, R, to follow this simple relation [7], 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 higher 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 ˙ω. 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.

Another effect predicted by General Relativity is that, if the total angular momentum vector is not aligned with the spin axis, the latter will precess about the orbit normal. The predicted periods for geodetic precession for PSR J0737−3039A and B are only 75 and 71 yr respectively. Because of that the geometry of the system is expected to change in a short time scale and this should result in secular changes in the observed pulse shape, because the line of sight across the emission beam changes. Somewhat surprisingly, observations of pulsar A show no significant evidence for profile-shape variation over a three-year interval [8]. Near alignment of A’s rotation axis with the orbit normal is a possible explanation for
the observed lack of variations.

3 A revised double neutron star coalescence rate.

The merging of a double-neutron-star system should produce a burst of emission of gravitational waves. Due to the energy budget and to the expected typical frequency of these events, they are among the primary targets for the current generation of ground-based gravitational waves detectors, which should be able to detect them up to a distance of about 20 Mpc. Hence, a key question is the occurrence rate of these double-neutron-star coalescences in a volume of universe of that radius. This rate can in turn be estimated on the basis of the rate of events in the Galaxy. Among the double-neutron-star systems previously known, only three had 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 [9]. Also, recent studies [10] have demonstrated that the current estimate of the Galactic merger rate $R$ relies mostly on PSR B1913+16 characteristics. One can hence start by

![Graph](image_url)

Figure 2: Probability density function of the actual double neutron star binary merger rate in the Galaxy (bottom axis) and the predicted initial LIGO detector rate (top axis). The solid line shows the total probability density. Dashed lines show those obtained for each of the three merging binary systems considered. Inset: Total probability density, and corresponding 68%, 95%, and 99% confidence limits, shown in a linear scale [3].
The double Pulsar J0737–3039A/B comparing the observed properties of B1913+16 and J0737–3039A/B systems. The latter will merge due to the emission of gravitational waves in ~ 85 Myr, a time-scale 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 ionized gas in the interstellar medium; [11]) 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 as \( R_k = N_k/\tau_k \) [10]. Here \( \tau_k \) 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 \( [\tau_{1913}/\tau_{0737} = (365 \text{ Myr})/(185 \text{ Myr})] \) 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 \( L_{400} = 30 \text{ mJy kpc}^2 \) 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 \( R_{0737}/R_{1913} \sim 12 \). 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 [3] give results consistent with this simple estimate and show that the peak of the merger rate increase factor resulting from the discovery of J0737–3039A/B system lies in the range 5-7 (Fig. 2) and is largely independent of the adopted pulsar population model. For the reference model (model nr. 6 of [10]), the updated cosmic detection rate for first generation gravitational-wave detectors is about one every three years (for initial LIGO; two per year with advanced LIGO). 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.

References


