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The Highly Relativistic Binary Pulsar PSR J0737−3039A: Discovery and Implications

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Abstract. PSR J0737−3039A is a millisecond pulsar with a spin period of 22.7 ms in a double-neutron-star system with an orbital period of 2.4 hours. Its companion has also been detected as a radio pulsar, making this binary the first known double-pulsar system. Its discovery has important implications for tests of relativistic gravity, gravitational-wave detection, and plasma physics. Here we briefly describe the discovery of the first pulsar in this unique system and we present the first results obtained from follow-up studies.

1. Introduction

Since the discovery of the first binary pulsar (Hulse & Taylor 1975), the detection of two active pulsars in the same binary system has been a primary aim of any pulsar survey. We summarize here the basic steps which eventually led to the discovery of this long-sought system and we report on the first implications for gravitational-wave detection. Papers by Kramer et al. and Manchester et al. (in this volume) will give more details on the second discovered pulsar, dealing with the opportunity to use this binary as a magnificent laboratory for relativistic gravity and for investigating magnetospheric processes.

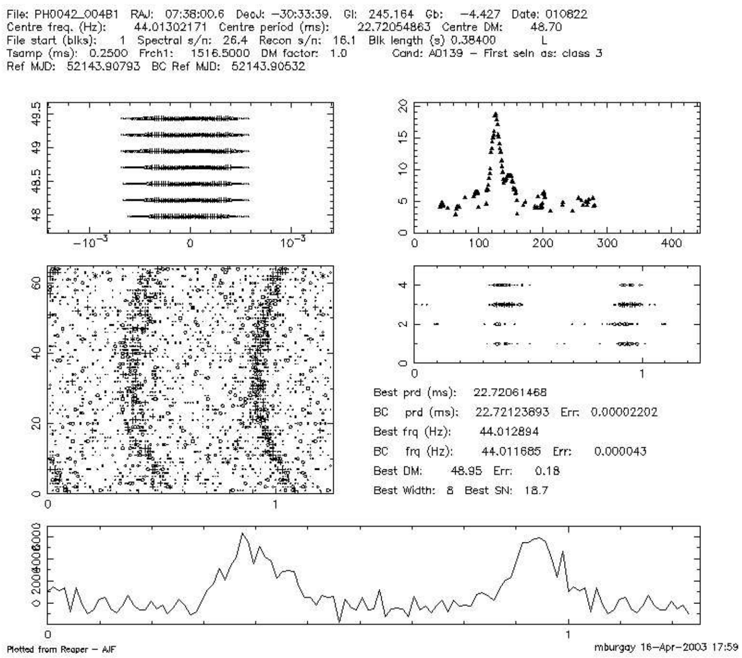

Figure 1. Original detection plot for PSR J0737−3039A. The pulsar was detected in the 11th beam (beam B) of the multibeam receiver of the Parkes 64 meter radiotelescope with a signal-to-noise ratio of 18.7. The offset between the sky coordinates of the centre of the beam and the (subsequently determined) position of PSR J0737−3039A is 6.′3.

2. Discovery

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). The original detection plot is shown in Figure 1, reporting a signal-to-noise ratio of 18.7. A higher signal-to-noise ratio of 26.3 resulted from the same observation for the first harmonic of the pulse period (11.3 ms), due to the similar energy contribution and roughly half-phase separation of the two peaks in the profile displayed in Figure 1; the pulse period ambiguity was easily solved as soon as further, longer observations became available (a high resolution pulse profile for PSR J0737−3039A is presented in Manchester et al., in this volume).

From the very pronounced curvature in the spin phase vs sub-integrations box (central panel on the left in Fig. 1), indicating a time-dependent change in the phase of arrival of the pulses, it was immediately clear that the pulsar signal was affected by a significant Doppler effect. This, in turn, suggested that the pulsar was experiencing the gravitational pull of a nearby and relatively massive companion.

Using a code suitable for searching strongly accelerated pulsars, we found the best correction to the Doppler phase shift for an acceleration of 99 $\mathrm{m/s^2}$, suggesting a binary period of just a few hours for a companion of $\sim 1\,M_\odot$. Follow-up observations performed in May 2003, consisting of three $\sim 5\,$hr integrations, confirmed that the orbit is indeed very tight and far from circular: the binary period P_b is only 2.4 hr and the eccentricity $e \simeq 0.09$. This makes the orbit of J0737−3039A the tightest among all known binary pulsars in eccentric systems. Figure 2 shows the radial velocity curve obtained by plotting the barycentric spin period of the pulsar, measured at different times, versus the binary phase: the fact that the orbit is eccentric is easily seen from the asymmetric shape of the curve.

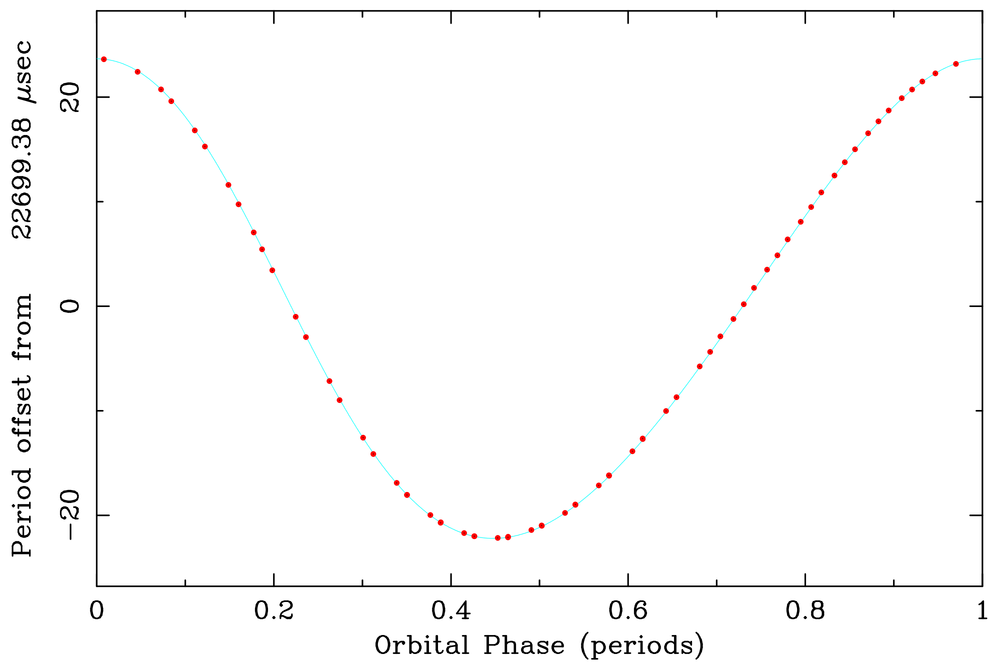

Figure 2. The original radial velocity plot for PSR J0737−3039A, obtained from follow-up observations taken at Parkes in early May 2003.

From the approximate orbital parameters available after two days of follow-up observations ($P_\mathrm{b} \simeq 2.4\,$hr, $a \sin i \simeq 1.4\,$lt-s; for the current best estimates of these parameters see Table 1 of Kramer et al., in this volume), the pulsar mass function was calculated to be $M_\mathrm{f} = 0.29\,M_\odot$, implying a minimum companion mass of about $1.24\,M_\odot$ assuming a neutron star mass $M_\mathrm{NS} = 1.35\,M_\odot$. Accordingly, the companion star could be a nondegenerate object, a massive Carbon-Oxygen white dwarf (CO-WD) or a second neutron star. The first hypothesis was immediately ruled out since the radius of a nondegenerate object of the required mass would almost completely fill the orbit of the system, probably strongly affecting the radio emission, which is not seen in the signal of PSR J0737−3039A. A CO-

WD companion also appeared unlikely considering the eccentricity of the orbit: a binary containing a recycled neutron star and a white dwarf is indeed expected to be highly circular since it had the time to reach the minimum energy configuration (i.e., to circularize). However, if a second, recent supernova explosion has occurred forming another neutron star, the energy and momentum released can have distorted the system and this would explain the observed eccentricity.

A further strong constraint on the nature of the PSR J0737−3039A companion came a few days later from the first fit of a binary model to the timing data. 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 turned out to have a remarkably high value: $\dot{\omega} \simeq 17^\circ$/yr (note that the previously highest observed value was 5.33°/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 $1.24\,M_\odot$. While the maximum mass for the pulsar perfectly agrees with the other measurements of neutron star masses (Thorsett & Chakrabarty 1999), the mass of the companion is a little lower than expected. In the absence of additional information the white dwarf hypothesis could not be completely rejected. It is important to point out, however, that the $\dot{\omega}$ value that one measures, in general, is given by the usual relativistic expression plus two extra classical terms, arising from *(i)* tidal deformations of the companion star (relevant only if the companion is nondegenerate), and *(ii)* from the rotationally-induced quadrupole moment of the companion star (for the case of a fast rotating white dwarf). For a neutron star both additional contributions are negligible. If the companion to J0737−3039A were a white dwarf, the relativistic $\dot{\omega}$, and by consequence the total system mass, would be smaller (since $\dot{\omega}_{\rm GR} = \dot{\omega}_{\rm obs} - \dot{\omega}_{\rm cl}$), implying an implausibly small ($\lesssim 1\,M_\odot$) maximum allowed mass for the pulsar. All this strongly suggested that the discovered binary was the sixth, and by far most relativistic, double-neutron-star (DNS) system known. The ultimate confirmation of this interpretation came a few months later when, while analyzing the follow-up observations of PSR J0737−3039A, a strong periodic signal with a 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 just been discovered.

3. Determination of Post-Keplerian Parameters

In the double-pulsar system, the relativistic effects are highly enhanced, thanks to the short orbital period and high orbital inclination. That makes it an excellent laboratory for studying relativistic gravity. Using only the follow-up observations of pulsar A, we have been able, in less than a year of regular timing, to measure four Post-Keplerian (PK) parameters, whose values are listed in Table 1 of Kramer et al. (in this volume): besides the already mentioned parameter $\dot{\omega}$, we have measured γ (combining gravitational redshift and time dilation) and the parameters r and $s \equiv \sin i$. The latter represent, respectively, the range and the shape of the Shapiro delay, measuring the time delays of the signal caused by the spacetime deformations around the companion star. Having measured four PK parameters, we succeeded in performing two independent tests of general relativity (see Kramer et al. for details) after less than 8 months of observations using pulsar A only. The fifth PK parameter, the orbital decay, should be determined by the end of 2004. The detectability of pulsar B makes this system even more promising, providing further unprecedented tests of gravity theories, as explained by Kramer et al. (in this volume).

4. Gravitational-Wave Detection

The discovery of a binary system with the characteristics of J0737−3039 implies a significant increase in the Galactic DNS coalescence rate $\mathcal{R}$ and, in turn, in the gravitational-wave detection rate for ground-based observatories such as LIGO, GEO and VIRGO (Burgay et al. 2003; Kalogera et al. 2004; Kim et al., in this volume).

Pulsars A and B will coalesce due to the emission of gravitational waves in a merger time $\tau_{\rm m} \simeq 85\,{\rm Myr}$, a factor 3.5 shorter than that for PSR B1913+16 (Taylor, Fowler, & McCulloch 1979). In addition, the estimated distance to J0737−3039 ($\sim 600\,{\rm pc}$, with an intrinsic uncertainty of about 50% from the dispersion measure; $\sim 1\,{\rm kpc}$ from X-ray absorption) is an order of magnitude less than the distance to PSR B1913+16. These properties have a substantial impact on the predicted 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 $\mathcal{R}_k \propto N_k/\tau_k$ (Kim, Kalogera & Lorimer 2003). Here τ_k is the binary pulsar lifetime defined as the sum of the time since birth, $\tau_{\rm b}$, and the remaining time before coalescence, $\tau_{\rm m}$, whereas N_k is the scaling factor, defined as the number of binaries in the Galaxy belonging to the given class. The value of $\tau_{\rm b}$ for pulsar A can be computed as the time since the pulsar left the spin-up line (as calculated by Arzoumanian, Cordes, & Wasserman 1999), which gives $\tau_{\rm b} \simeq 150\,{\rm Myr}$. Alternatively, one can assume that the characteristic age of pulsar B is a reliable estimate of the true age of both pulsars. In this case we get $\tau_{\rm b} \simeq 50\,{\rm Myr}$. In either case the lifetime of this system is much shorter than that of PSR B1913+16 ($\tau_{1913}/\tau_{0737} \simeq 1.6 - 2.7$, implying roughly a doubling of the ratio $\mathcal{R}_{0737}/\mathcal{R}_{1913}$.

A much more substantial contribution to the increase factor comes from the comparison of the pulsars' luminosities. Assuming conservatively a distance of 1 kpc (as suggested by the X-ray observations; see McLaughlin et al. 2004), the pulsed luminosity at 400 MHz of the J0737-3039 binary system is $L_{0737} \sim 30\,{\rm mJy\,kpc^2}$, much lower than that of PSR B1913+16 ($\sim 200\,{\rm mJy\,kpc^2}$). For a planar homogeneous distribution of pulsars in the Galaxy, the ratio N_{0737}/N_{1913} scales as $L_{1913}/L_{0737} \simeq 6$. Therefore we obtain $\mathcal{R}_{0737}/\mathcal{R}_{1913} \simeq 12$. Including the moderate contribution of the longer-lived PSR B1534+12 system to the total rate (van den Heuvel & Lorimer 1996; Arzoumanian et al. 1999; Kalogera et al. 2001; Kim et al. 2003), we obtain an increase factor for the total merger rate $(\mathcal{R}_{0737} + \mathcal{R}_{1913} + \mathcal{R}_{1534})/(\mathcal{R}_{1913} + \mathcal{R}_{1534})$ of about an order of magnitude. Similar results have been obtained by Kim et al. (in this volume) with a different approach.

This means that ground-based gravitational-wave detectors such as LIGO, GEO, or VIRGO should be able to detect a burst of gravitational waves produced in a DNS merger event once every few years instead of once in a few decades, with important consequences for the gravitational-wave community.

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