A&A manuscript no.
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06 (08.14.1; 08,16,6; 08,02,3; 08,05,3; 08,13.2)

ASTRONOMY AND ASTROPHYSICS
21.12.2017

PSR J2019+2425: A Unique Testing Ground for Binary Evolution

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Received 19 December 1997 / Accepted 26 March 1998

Abstract. If the theoretical relationship between white dwarf mass and orbital period for wide-orbit binary radio pulsars is assumed to be correct, then the neutron star mass of PSR J2019+2425 is shown to be $\sim 1.20 M_{\odot}$. Hence the mass of the neutron star in this system prior to the mass transfer phase is expected to have been $< 1.1 M_{\odot}$. Alternatively this system descends from the accretion induced collapse (AIC) of a massive white dwarf.
We estimate the magnetic inclination angles of all the observed wide-orbit low-mass binary pulsars in the Galactic disk using the core-mass period relation and assuming that the spin axis of an accreting neutron star aligns with the orbital angular momentum vector in the recycling process of the pulsar. The large estimated magnetic inclination angle of PSR J2019+2425, in combination with its old age, gives for this system evidence against alignment of the magnetic field axis with the rotational spin axis. However, in the majority of the similar systems the distribution of magnetic inclination angles is concentrated toward low values (if the core-mass period relation is correct) and suggests that alignment has taken place.

Key words: binaries: evolution, mass-loss, compact stars – stars: neutron – pulsars: general, formation

A correlation between orbital period and companion white dwarf mass has often been proposed to exist among low-mass binary pulsars (hereafter LMBPs). However, it has been demonstrated (Tauris 1996) that observations of wide-orbit LMBPs are difficult to fit onto the theoretical relation proposed originally by Joss et al. (1987). In this letter we look at the consequences for the population of LMBPs under the assumption that the theoretical relation is correct. For a review on the formation and evolution of binary millisecond pulsars, see Bhattacharya & van den Heuvel (1991).

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If the orbital period after the formation of a neutron star is relatively large ($\gtrsim$ a few days), then the subsequent mass transfer is driven by the interior nuclear evolution of the companion star after it evolved into a (sub)giant and loss of orbital angular momentum by gravitational wave radiation and/or magnetic braking can be neglected. In this case we get a low-mass X-ray binary (LMXB) with a (sub)giant donor. These systems have been studied by Webbink et al. (1983), Taam (1983) and Joss et al. (1987). If mass is transfered from a less massive companion star to the more massive neutron star, the orbit expands and a stable mass transfer is achieved as the donor ascends the giant branch. Since the radius of such a donor star is a simple function of the mass of the degenerate helium core, $M_{\rm core}$, and the Roche-lobe radius, $R_{\rm L}$, only depends on the masses and separation between the two stars, it is clear that the final orbital period ($40^{\rm d} \lesssim P_{\rm orb}^{\rm f} \lesssim 1000^{\rm d}$) of the resulting binary will be a function of the final mass ($0.20 \lesssim M_{\rm WD}/M_{\odot} \lesssim 0.45$) of the helium white dwarf companion.

The relation between the orbital period of the recycled pulsar and the mass of its white dwarf companion was recently re-derived by Rappaport et al. (1995) using refined stellar evolution calculations:

$$P_{\rm orb} = 0.374 \left[\frac{R_0 M_{\rm WD}^{4.5}}{1 + 4M_{\rm WD}^4} + 0.5 \right]^{3/2} M_{\rm WD}^{-1/2} \qquad (1)$$

where $P_{\rm orb}$ is given in units of days and $M_{\rm WD}$ is expressed in units of solar masses and $3300 < R_0/R_{\odot} < 5500$ is an adjustable constant which depends on the composition of the donor star (the progenitor of the white dwarf).
In Table 1 we have compared observational data with the core-mass period relation given in eq. (1) and derived the expected white dwarf mass and orbital inclination angle in each of the 10 wide-orbit LMBPs in the Galactic disk, assuming two different values for the neutron star mass, $M_{\rm NS}$, and using the observed mass functions defined by:

$$f\,(M_{\rm NS}, M_{\rm WD}) = \frac{(M_{\rm WD} \sin i)^3}{(M_{\rm NS} + M_{\rm WD})^2} = \frac{4\pi^2}{G} \, \frac{(a_{\rm p} \sin i)^3}{P_{\rm orb}^2} \qquad (2)$$

Table 1. Observed wide-orbit (class A) low-mass binary pulsars in the Galactic disk.

					$M_{NS} = 1.4M_\odot$			$M_{NS} = 1.8M_\odot$		
PSR-name	P_{orb}	P_{spin}	f	M_{WD}^{PMc}	$M_{WD}^{i=60^\circ}$	M_{WD}^{min}	i^{PMc}	$M_{WD}^{i=60^\circ}$	M_{WD}^{min}	i^{PMc}
B0820+02	1232^d	865 ms	0.003 $M_\odot$	0.500 $M_\odot$	0.231 $M_\odot$	0.197 $M_\odot$	26.3°	0.271 $M_\odot$	0.232 $M_\odot$	30.2°
J1455-3330	76.2^d	7.99 ms	0.0063 $M_\odot$	0.305 $M_\odot$	0.304 $M_\odot$	0.259 $M_\odot$	59.9°	0.356 $M_\odot$	0.303 $M_\odot$	84.2°
J1640+2224	175^d	3.16 ms	0.0058 $M_\odot$	0.351 $M_\odot$	0.295 $M_\odot$	0.251 $M_\odot$	48.0°	0.345 $M_\odot$	0.294 $M_\odot$	58.5°
J1643-1224	147^d	4.62 ms	0.00078 $M_\odot$	0.341 $M_\odot$	0.142 $M_\odot$	0.122 $M_\odot$	23.0°	0.167 $M_\odot$	0.144 $M_\odot$	26.7°
J1713+0747	67.8^d	4.57 ms	0.0079 $M_\odot$	0.299 $M_\odot$	0.332 $M_\odot$	0.282 $M_\odot$	71.6°	0.388 $M_\odot$	0.330 $M_\odot$	—
J1803-2712	407^d	334 ms	0.0013 $M_\odot$	0.407 $M_\odot$	0.170 $M_\odot$	0.146 $M_\odot$	23.5°	0.200 $M_\odot$	0.172 $M_\odot$	27.1°
B1953+29	117^d	6.13 ms	0.0024 $M_\odot$	0.328 $M_\odot$	0.213 $M_\odot$	0.182 $M_\odot$	36.0°	0.250 $M_\odot$	0.214 $M_\odot$	42.5°
J2019+2425	76.5^d	3.93 ms	0.0107 $M_\odot$	0.305 $M_\odot$	0.373 $M_\odot$	0.316 $M_\odot$	—	0.435 $M_\odot$	0.369 $M_\odot$	—
J2033+1734	56.2^d	5.94 ms	0.0027 $M_\odot$	0.290 $M_\odot$	0.222 $M_\odot$	0.190 $M_\odot$	43.0°	0.261 $M_\odot$	0.223 $M_\odot$	51.8°
J2229+2643	93.0^d	2.98 ms	0.00084 $M_\odot$	0.315 $M_\odot$	0.146 $M_\odot$	0.125 $M_\odot$	25.4°	0.171 $M_\odot$	0.147 $M_\odot$	29.6°

M_{WD}^{PMc} : mass of the white dwarf as expected from the core-mass period relation – cf. eq.(1). We assumed $R_0 = 4950R_\odot$.

$M_{WD}^{i=60^\circ}$: mass of the white dwarf assuming an inclination angle, $i = 60^\circ$ of the binary system.

M_{WD}^{min}: mass of the white dwarf assuming an inclination angle, $i = 90^\circ$ of the binary system.

i^{PMc} : orbital inclination angle of the system in order to obtain $M_{WD} = M_{WD}^{PMc}$.

A horizontal dash means that any inclination angle is inconsistent with such a high mass for the neutron star (i.e. $\sin i > 1$).

The recycling process is assumed to align the spin axis of the neutron star with the orbital angular momentum vector as a result of $\sim 10^8$ yr of stable disk accretion. Hence the orbital inclination angle, i, is equivalent to (on average) the magnetic inclination angle, α, defined as the angle between the spin axis and the center of the pulsar beam (*viz.* line-of-sight).

Wide-orbit LMBPs form a distinct class of binary millisecond pulsars (class A) and are expected to have helium white dwarf companions – cf. Tauris (1996). For helium white dwarf companions in the interval $0.17 < M_{WD}/M_\odot < 0.45$, we notice that the mass of the white dwarf can be conveniently found from the following formula:

$$M_{WD} = \left(\frac{550P_{orb}^4}{R_0^6}\right)^{1/23} \tag{3}$$

which is a simple fit to eq. (1) with an error of less than 1% in the entire mass interval, independent of R_0[1].

By combining the above equations is is possible to calculate M_{NS} as a function of i and R_0. For PSR J2019+2425 the mass of the neutron star is constrained to be remarkably low. This is shown in Fig. 1. A weak interpulse is seen in the pulse profile of PSR J2019+2425 (Nice, Taylor & Fruchter 1993) which indicates that α, and hence i, is large. Though such a pulsar profile could possibly be explained from a wide one-pole emission beam (Manchester 1997), we shall assume $65^\circ < i < 90^\circ$. We find that the value of R_0 is most likely to be in the interval: $4950 < R_0/R_\odot < 5500$ – i.e. the progenitor of the white dwarf is

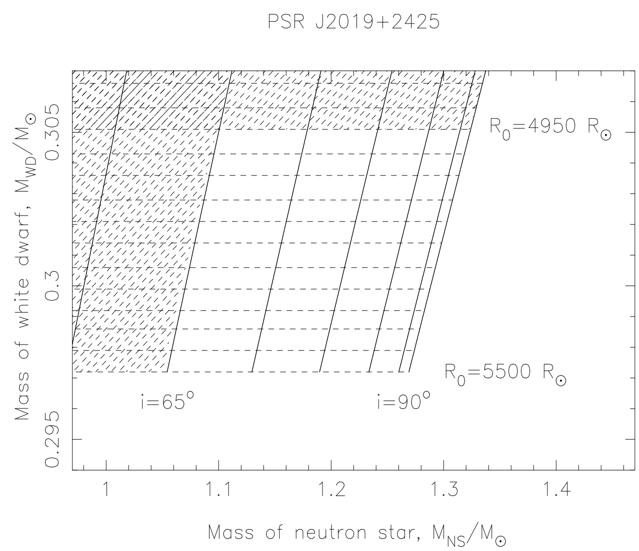

Fig. 1. The expected mass of the pulsar PSR J2019+2425 as a function of R_0 (in units of $R_\odot$) and orbital inclination angle, i.

[1] For very small values of R_0 ($\sim 3300R_\odot$) the above fit is only accurate to within 1% in the mass interval $0.20 < M_{WD}/M_\odot < 0.45$.

either a pop. I star or an "intermediate" pop. I+II star, cf. Rappaport et al. (1995). Though the extremely large intrinsic characteristic age, $\tau_{\rm i} = 27$ Gyr of PSR J2019+2425 (Camilo, Thorsett & Kulkarni 1994) could suggest a progenitor star with pop. II abundances, we find it unlikely given the fact that the binary is located in the Galactic disk ($|z| = 100$ pc). If this is correct, it leaves us with a neutron star mass of $M_{\rm NS} = 1.20 \pm 0.10 M_\odot$ as our best guess.

It has been suggested by van den Heuvel & Bitzaraki (1995) that the neutron star in PSR J2029+2425 might have accreted as much as 0.65 $M_\odot$ in order to explain its present low magnetic field strength, $B = 1.8 \times 10^8$ Gauss. However, in order to avoid a pre-accretion neutron star mass of barely $M_{\rm NS}^{\rm pre-acc} = 1.20 M_\odot - 0.65 M_\odot \approx 0.6 M_\odot$ we suggest that the neutron star only has accreted $\sim 0.10 M_\odot$. Another constraint on the maximum amount of matter accreted, and hence on the minimum value of $M_{\rm NS}^{\rm pre-acc}$, is the fact that this wide-orbit system is expected to have evolved though an X-ray phase with stable Roche-lobe overflow and hence $M_{\rm NS}^{\rm pre-acc} \gtrsim M_2$ (where M_2 is the mass of the white dwarf progenitor). However, we must require $M_2 > 1.1 M_\odot$, given the large cooling age of 8–14 Gyr of this system (Hansen & Phinney 1998), in order for the companion to evolve in a time less than the age of our Galaxy ($\tau_{\rm MS} + \tau_{\rm cool} < \tau_{\rm gal}$). Therefore we also conclude that the neutron star accreted less than 15% of the transfered matter ($\Delta M = M_2 - M_{\rm WD} > 0.80 M_\odot$) – i.e. $\beta > 0.85$ (where β is the fraction of the transfered matter lost from the system). This is interesting since the mass loss rate of the donor star, $\dot{M}_2$, in a system like PSR J2019+2425 is expected (Verbunt 1990) to have been less than the Eddington accretion limit, $\dot{M}_{\rm Edd} \approx 1.5 \times 10^{-8} M_\odot {\rm yr}^{-1}$.

In Fig. 2 we have plotted the distribution of estimated magnetic inclination angles, α, from Table 1, assuming $M_{\rm NS} = 1.4 M_\odot$ and $\alpha = i$ (see above). There is seen to be a concentration toward low values of α in the observed distribution. This is in agreement with the recent result obtained by Backer 1998 (cf. his Fig.3) who analysed the distribution of observed minimum companion masses[2]. Our result remains valid for other choices of $M_{\rm NS}$ and R_0 which only yield slight changes of the distribution. Since pulsars with small values of α generally shine on a smaller fraction of the celestial sphere (simply due to geometry) it is clear that the true underlying parent distribution is even further skewed toward small values of α. If the distribution of α (and thus i) was random, we would expect $\langle\alpha\rangle = 60°$ for the parent population and $\langle\alpha\rangle > 60°$ for the observed distribution. Also keep in mind that systems where α is smaller than the beam radius, ρ, can be very difficult to detect due to lack of, or very little, modulation of the pulsed signal. This could explain why no observed systems have $\alpha < 20°$.

For normal non-recycled pulsars there is no anti-

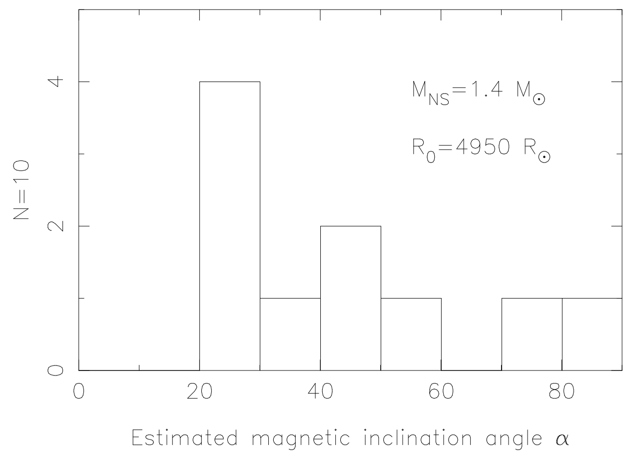

Fig. 2. The distribution of estimated inclination angles in the wide-orbit LMBPs listed in Table 1, using the core-mass period relation.

correlation between radio luminosity and α in a sample of 350 pulsars where polarization studies have provided α (Tauris & Manchester 1998). Therefore there is no reason to believe that binary millisecond pulsars are more easily detected when α is small.

Tauris & Manchester (1998) have presented some evidence for alignment of the magnetic field axis with the spin axis of normal non-recycled pulsars. Such a mechanism could also operate in recycled pulsars and would be able to explain this non-random distribution of inclination angles. This could also explain why $\tau_{\rm i}$ often exceeds the age of our Galaxy, since alignment after the accretion process results in a braking index of $n > 3$ and therefore also in a deviation of $\tau_{\rm i}$ from the true age (Manchester & Taylor 1977). However, in the case that alignment occurs in all recycled pulsars, PSR J2019+2425 should be younger (due to its large value of α) than the bulk of the other wide-orbit LMBPs. This is in contradiction to the very large cooling age of this system (see above) and the large value of $\tau_{\rm i}$ observed in this system compared to that of the other systems – although $\tau_{\rm i}$ is only a rough age estimator individual to each system. Alternatively, it is possible that there is an initial bifurcation angle above which the (accretion) torque acting on the neutron star results in a nearly perpendicular configuration after (or during) the mass transfer process (van den Heuvel, private communication).

It should be noticed, that if alignment occurs in the majority of binary millisecond pulsars this would enhance the birthrate problem between LMXBs and LMBPs (Kulka-

[2] However, we disagree with his suggestion of a preference for orthogonal magnetic and spin axes. Such configurations would also exacerbate the already existing problem between the theoretical core-mass period relation and observations of wide-orbit LMBPs (Tauris 1996).

rni & Narayan 1988) since pulsars with smaller magnetic inclination angles in average shine on a smaller part of the sky and hence their Galactic population must be even larger.

An alternative model for the formation of PSR J2029+2425 is that this system descends from the accretion induced collapse of a massive O-Ne-Mg white dwarf (e.g. Nomoto & Kondo 1991). In such a scenario the neutron star might have accreted only a very little amount of matter after its formation and the orbital angular momemtum axis need not be aligned with the spin axis of the neutron star. Also eq. (1) might not apply in this case and thus we have no simple constraint on the lower limit to the mass of the neutron star.

Future observations of the shape and range of the general relativistic Shapiro delay in PSR J2019+2425 would yield i and $M_{\rm WD}$. The mass function would then give a value for the neutron star mass as well. These masses are highly desired in order to test theories for understanding the formation and evolution of binary millisecond pulsars.

Acknowledgements. The author thanks Ed van den Heuvel for discussions and many helpful comments on the manuscript. This research was supported in part by the NWO Spinoza-grant SPI 78-327.

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