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An evolutionary model for the gamma-ray system PSR J1311−3430 and its companion

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ABSTRACT

The most recent member of the millisecond pulsar with very low mass companions and short orbital periods class, PSR J1311−3430 (Pletsch et al. 2012) is a remarkable object in various senses. Besides being the first discovered in gamma rays, its measured features include the very low or absent hydrogen content. We show in this Letter that this important piece of information leads to a very restricted range of initial periods for a given donor mass. For that purpose, we calculate in detail the evolution of the binary system self-consistently, including mass transfer and evaporation, finding the features of the new evolutionary path leading to the observed configuration. It is also important to remark that the detailed evolutionary history of the system naturally leads to a high final pulsar mass, as it seems to be demanded by observations.

Key words: binaries: close – stars: evolution – pulsars: general – pulsars: individual: PSR J1311−3430.

1 INTRODUCTION

The discovery of the 2 ms, 93 min orbit, 'black widow' (BW) pulsar PSR J1311−3430 in gamma rays (Pletsch et al. 2012) comes to increase the number of such systems in a very interesting fashion. This is the first time that gamma-ray pulsations led to an identification without the need of low-energy counterparts, and additional work (Romani et al. 2012) indicated the absence or very low level of H in the companion, plus the suggestive evidence of a large mass of the pulsar itself. These facts are quite important to reconstruct the evolutionary path that led to the present state.

In a former work (Benvenuto, De Vito & Horvath 2012), we have modelled a similar system, namely the binary millisecond pulsar PSR J1719−1438 in a 2.2 h orbit featuring a very low mass companion (Bailes et al. 2011). We shall show now that the additional information gathered from PSR J1311−3430 is useful to refine the models and restrict the possible initial states to a rather small range, for a given assumed value of the initial donor mass.

We have described the features and tests of the evolutionary code employed in these studies elsewhere (see Benvenuto et al. 2012 and references therein). A simultaneous integration of the stellar structure, mass transfer rate (if any) and orbit evolution is performed taking into account (i) *accretion* on to the neutron star (NS), (ii) the *evaporating wind* driven by the pulsar radiation and (iii) the *irradiation feedback*, present when the donor star that transfers mass on to the NS and accretion illuminates the donor star modifying its evolution (see Büning & Ritter 2004 for further details on this item).

The three effects have been shown to be important for the evolution of PSR J1719−1438. The case of PSR J1311−3430 adds considerable new information to address because spectroscopic/photometric data have shown that H is almost absent (Romani et al. 2012), at the level of a number abundance $n_H < 10^{-5}$ in contrast with other members of the group,[1] and also that a high mass for the pulsar is favoured, depending somewhat on the interpretation of the light curve but bounded by $M_{\rm PSR} \geq 2.1\,{\rm M}_{\odot}$. We shall show now that the evolutionary models can match these and the rest of the observed parameters, constraining quite tightly the initial state of the system.

2 CALCULATIONS

The evolution of PSR J1311−3430 system has been modelled within the same scenario depicted in Benvenuto et al. (2012) starting

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[1] It corresponds to an H mass abundance $X < 2.5 \times 10^{-6}$ for a helium-dominated composition.

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with a normal, solar composition star and a just-formed NS orbiting together with an initial period $P_{\rm i} \lesssim 1$ d.

When the donor star radius R_2 equals the radius of the Roche lobe R_L,[2] it occurs the onset of the Roche lobe overflow (RLOF). Around this epoch tidal dissipation forces quickly circularize the orbit. The donor star transfers mass across the Lagrangian point L_1 towards the NS, causing the orbit to evolve. As in Podsiadlowski, Rappaport & Pfahl (2002), we have parametrized the uncertain fraction of mass effectively accreted by the NS with a quantity $\beta > 0$ (that is, $\dot{M}_1 = -\beta \dot{M}_2$), assuming that it is always below the Eddington limit $\dot{M}_{\rm Edd} = 2 \times 10^{-8}\ {\rm M}_{\odot}\ {\rm yr}^{-1}$. Since, in general, $\beta < 1$ some material is lost from the system, carrying away specific angular momentum of the secondary. Fortunately, the value of β is not critical in determining the evolution of this kind of systems (De Vito & Benvenuto 2012), and so we have assumed an average value of $\beta = 1/2$. Gravitational radiation (Landau & Lifshitz 1971) and magnetic braking (Verbunt & Zwaan 1981) are known to provide relevant angular momentum sinks. Additionally, the $\dot{M}_2$ due to RLOF has been described by the expressions given in Ritter (1988).

As stated in Benvenuto et al. (2012), this ‘standard’ prescription valid for LMXBs (Podsiadlowski et al. 2002) must be supplemented with a wind evaporation $\dot{M}_{2,\rm evap}$ law. Here, we shall assume the expressions given by Stevens, Rees & Podsiadlowski (1992), namely

$$\dot{M}_{2,\rm evap} = -\frac{f}{2v_{2,\rm esc}^2} L_P \left(\frac{R_2}{a}\right)^2, \quad (1)$$

where the spin-down luminosity L_P of the pulsar is given by $L_P = 4\pi I_1 P_1^3 \dot{P}_1$ (I_1 is the moment of inertia of the NS, P_1 is its period and $\dot{P}_1$ its spin-down rate), $v_{2,\rm esc}$ is the escape velocity from the donor star surface, a is the semi-axis of the circular orbit and f is an efficiency factor. As in Benvenuto et al. (2012), we shall set $f L_P = 0.04\,{\rm L}_{\odot}$. While irradiation feedback is a fundamental ingredient in computing the mass transfer evolution at early stages, we have found that it does not affect the evolutionary path of the system in the mass–orbital period plane. As we are interested here on the final evolution of the system, in this Letter we shall neglect irradiation feedback.

The evolution of the system has been computed with our detailed (Henyey) evolutionary code described in Benvenuto & De Vito (2003) and De Vito & Benvenuto (2012). We started with a fiducial donor mass of $2\,{\rm M}_{\odot}$ together with a $1.4\,{\rm M}_{\odot}$ NS, as in the case of PSR J1719−1438. The range of initial donor masses is bounded from below by the isolated-star evolution time-scale ($M_2 \approx 1.0\,{\rm M}_{\odot}$), which should be short enough to allow for the onset of mass transfer, and from above by $M_2 \geq 3.5\,{\rm M}_{\odot}$, because above that initial value the mass transfer is unstable (Podsiadlowski et al. 2002). As in the case of the evolution of PSR J1719−1438, $P_{\rm i}$ must be very short. However, extremely short $P_{\rm i}$ would cause the mass transfer to start at the zero-age main sequence, while too long $P_{\rm i}$ values would render a detached wide orbit after a few Gyr, not the observed BW-type system.

Even if these conditions are essentially the same as the ones we studied for PSR J1719−1438, the strong upper limit set by Romani et al. (2012) on the H abundance allows an important refinement of the models. Its solution rests on a delicate interplay between the dynamical evolution of the close binary system (CBS) and the structure of the donor star in a novel fashion, described as follows.

[2] We shall refer the NS (donor star) as the primary (secondary), with subindex 1 (2).

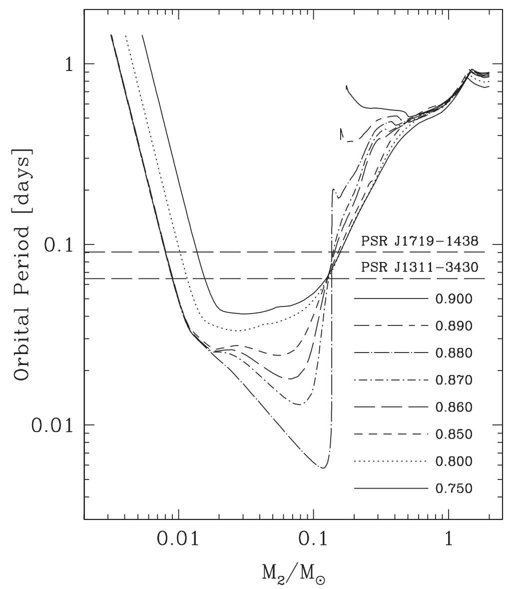

Figure 1. Orbital period−mass relation for the $2\,{\rm M}_{\odot}$ normal donor star evolving together with a $1.4\,{\rm M}_{\odot}$ NS for different values of the initial periods (in days). The observed orbital periods of PSR J1719−1438 and PSR J1311−3430 are denoted with dashed lines.

If the system started at low periods, around $P_{\rm i} = 0.7$ d, mass transfer starts when H core abundance is $X_c^{\rm RLOF} \approx 0.39$. From this initial condition on, T_c drops slowing down H burning. When $M_2 \approx 0.053\,{\rm M}_{\odot}$ the star becomes completely convective making it chemically homogeneous up to the photosphere with $X = 0.099$. Since for a larger $P_{\rm i}$ the onset of the RLOF occurs later, $X_c^{\rm RLOF}$ will have a lower value and X gets smaller. Eventually, there is a $P_{\rm i}$ value $P_{\rm i} \approx 0.86$ d for which $X_c^{\rm RLOF} = 0$, this condition holds for every period longer than that.

For this kind of CBSs, there exists a bifurcation period value $P_{\rm b}$: if $P_{\rm i} > P_{\rm b}$ the CBS evolves to an open configuration forming a low-mass helium white dwarf, while $P_{\rm i} < P_{\rm b}$ leads to the kind of BW systems we are interested in. For $P_{\rm i} < P_{\rm b}$, the minimum orbital period attained during evolution decreases when $P_{\rm i}$ increases.[3] This behaviour can be seen in Fig. 1, where for the system considered here the bifurcation period is between 0.880 and 0.890 d.

For $P_{\rm i} \lesssim P_{\rm b}$ there occur conditions for which $X_c^{\rm RLOF} = 0$ and mass transfer is able to remove most of H-rich outer layers. The donor star becomes a very low mass He star. Remarkably, such configuration leads to masses and orbital period in excellent agreement with observations. This tight interval $0.87 \lesssim P_{\rm i}/d \leq 0.90$ for PSR J1311−3430 is the only interval accepted in these calculations, a shorter $P_{\rm i}$ would produce H-rich BW systems. These features are clearly seen in Fig. 2.

We would like to emphasize that a large value of the pulsar mass (Romani et al. 2012) is a natural outcome of the evolution calculations, here restricted to a reasonable but uncertain initial value set to $M_1 = 1.4\,{\rm M}_{\odot}$ for definiteness. The evolution of the NS (pulsar) and donor star masses are depicted in Fig. 3. The final value of the NS mass is not sensitive to $P_{\rm i}$ as expected, and reflects the integrated

[3] This is due to the fact that the larger the $P_{\rm i}$, the star has a higher mean molecular weight μ. The star attains a partially degenerate interior at larger densities, a smaller Roche lobe and consequently a shorter orbital period. Partial degeneracy is a necessary condition for the orbit of the system to start to evolve to larger periods (Savonije, de Kool & van den Heuvel 1986).

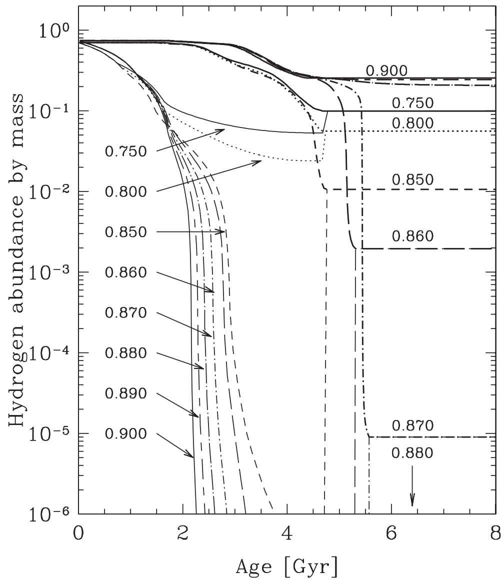

Figure 2. The evolution of the H abundance of the donor star at its centre (thin lines) and surface (thick lines) for the models included in Fig. 1. Depending on the value of the initial period, at a given age the star becomes fully convective being chemically homogeneous.

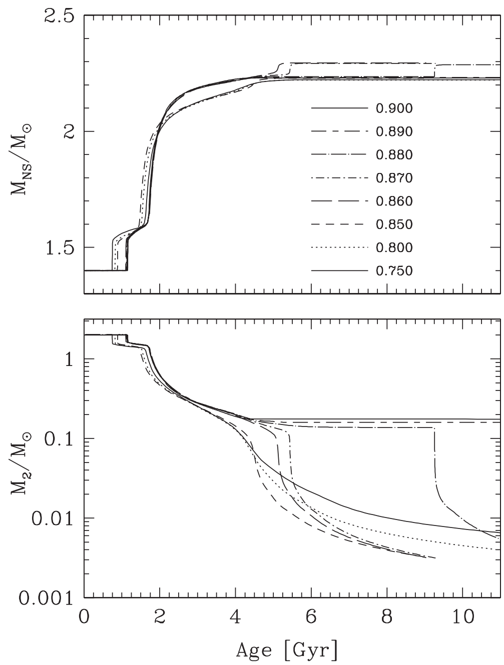

Figure 3. The evolution of the masses of the donor star (lower panel) and NS (upper panel) for the same systems included in Fig. 1. The labels of the different line types denote the values of the initial period (in days).

accretion over the system lifetime. While values $\geq 2.2\,M_\odot$ result, it should be kept in mind that the accretion efficiency parametrized by β was held fixed at 0.5 in all the calculation. A detailed modelling of the accretion could refine this rough time-average and eventually push the mass to higher values without any serious conflict with present observations. However, the problem of explaining the presence of very massive NS in these systems would call (Romani et al. 2012) for a major revision of current NS core microphysics (Horvath 2006; Lattimer & Prakash 2007).

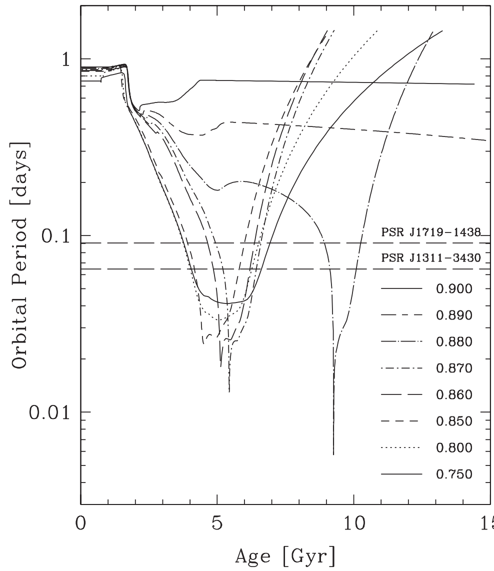

Figure 4. Orbital period evolution for the same systems included in Fig. 1.

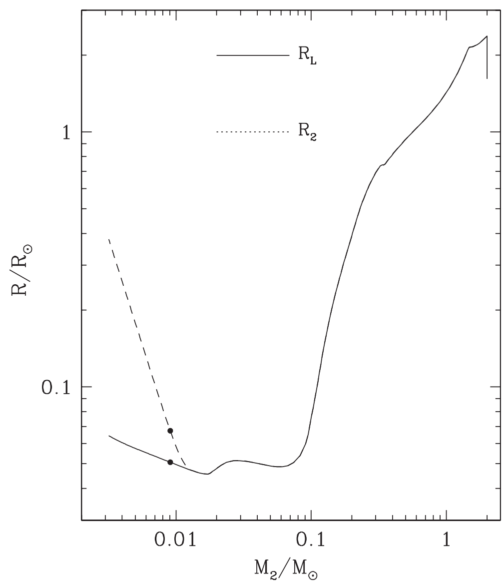

Figure 5. The radius of the donor star R_2 (solid lines) and its corresponding Roche lobe R_L (dashed lines) for the case of an initial period of 0.88 d. Points denote the conditions at which the system attains the orbital period of PSR J1311−3430 with low mass in detached conditions.

In Fig. 4, we show the period evolution for the considered CBSs. This figure, complementary of Fig. 1, provides the time-scale involved in the evolution of the CBSs. Finally, in Fig. 5 we show the evolution of the radius of the donor star and its corresponding Roche lobe for $P_{\rm i} = 0.88$ d, which represents a good model for PSR J1311−3430.

In Table 1, we present some relevant quantities for each of the computed models. From that, we see that all models with $P_{\rm i} < P_{\rm b}$ reproduce the main characteristics of BW systems. Particularly, the system containing the pulsar PSR J1311−3430 is best represented by models with $P_{\rm i} = 0.870$–0.880 d, just below the bifurcation value.

Let us briefly address the effect of the present uncertainties in the ingredients of the model. The value of $P_{\rm i}$ favoured for the occurrence of PSR J1311−3430 is dependent on the strength of the magnetic

Table 1. Some relevant characteristics of the binary systems when they reach the observed orbital period for *second* time. We list the initial period, the age, the donor and NS masses, the central temperature and density of the donor star, the orbital period, the surface H abundance, the radius of the Roche lobe, the radius and the mean density of the donor star. For the case of initial periods above bifurcation we list these quantities at the age of 13 Gyr.

$P_{\rm i}$ (d)	Age (Gyr)	$M_{\rm d}$ (10^{-3} M$_\odot$)	$M_{\rm NS}$ (M$_\odot$)	$\log T_c$ (K)	$\log \rho_c$ (g cm^{-3})	$P_{\rm orb}$ (10^{-2} d)	X	R_L (10^{-2} R$_\odot$)	R_* (10^{-2} R$_\odot$)	$\log \bar{\rho}_{\rm d}$ (g cm^{-3})
0.75	6.615	15.6	2.22	6.185	2.631	6.45	0.099	8.16	6.62	76.2
0.80	6.270	11.5	2.22	5.880	2.671	6.45	0.056	7.42	5.71	87.5
0.85	5.804	9.02	2.22	5.394	2.676	6.45	0.011	6.83	5.18	91.3
0.86	6.195	9.08	2.29	5.357	2.704	6.45	0.002	6.79	5.08	97.6
0.87	6.432	8.99	2.29	5.339	2.706	6.45	9×10^{-6}	6.76	5.05	98.4
0.88[a]	10.08	8.98	2.28	5.333	2.705	6.45	0.00	6.76	5.05	98.3
0.89[b]	13.00	157	2.23	7.037	4.996	36.5	0.241	53.8	3.43	5500
0.90	13.00	175	2.22	6.986	5.119	72.4	0.254	87.6	2.93	9747

[a]Largest initial period below bifurcation.
[b]Smallest initial period above bifurcation.

braking. We have tested it by introducing a factor lower than 1 in the standard expression. If the strength is half of the standard one, the whole scenario is essentially unchanged; the favoured period is 0.76 d and companions to BWs without H are possible. However, if magnetic braking were four times less efficient, it is still possible to find systems with the observed period but in all cases the companion retains some H. Thus, if so, a model for PSR J1311−3430 would be not possible. Regarding the value of the parameter fL_P, work in progress shows that if it were larger than assumed here, the qualitative behaviour of the evolution would be essentially the same, but the final evolution to large orbital periods would be markedly faster posing no problem for the whole model.

Performing a detailed calculation of the probability of having BWs without (or trace) H is beyond the scope of this Letter. However, in order to make some preliminary estimations, we have computed several models for the range of periods that evolve to BW configuration. We found that for a standard magnetic braking, systems evolving to BW have $0.500 \leq P_{\rm i}/d \leq 0.887$, being $0.873 \leq P_{\rm i}/d \leq 0.887$ for $X < 10^{-5}$ ($0.865 \leq P_{\rm i}/d \leq 0.887$ for $X < 10^{-3}$). Meanwhile, for the case of magnetic braking with half of the standard strength, the range of $P_{\rm i}$ evolving to BWs is $0.500 \leq P_{\rm i}/d \leq 0.769$, being $0.760 \leq P_{\rm i}/d \leq 0.769$ for $X < 10^{-5}$ ($0.753 \leq P_{\rm i}/d \leq 0.769$ for $X < 10^{-3}$). So, if the initial distribution of $P_{\rm i}$ were uniform, we would have 6 per cent of the BWs with $X < 10^{-3}$ and 3 per cent with $X < 10^{-5}$ for both, the standard magnetic braking strength and a half of it.

3 CONCLUSIONS

A new path for CBSs evolving into millisecond pulsar-very low mass companion final states has been studied and applied to the case of PSR J1719−1438 in Benvenuto et al. (2012). In this Letter, we have applied the same ideas to the latest member just discovered in gamma rays (Pletsch et al. 2012), namely the system PSR J1311−3430. These self-consistent calculations including all three essential ingredients (accretion, winds and illumination) show that theory is able to account for the formation of BW systems with He-dominated donor composition on a few Gyr time-scale.

The initial conditions for the particular case of PSR J1311−3430 are tightly bound from below by the requirement that $X < 2.5 \times 10^{-6}$, as displayed in Fig. 2. We also assert that the same evolution leading the system to the observed region of $P_{\rm orb}-M_2$ plane produces a high-mass pulsar as indicated by dedicated observations by Romani et al. (2012). Figs 1–5 display the evolution of the system at a glance.

We have finally checked that a variation of the initial donor mass M_2 within the whole interval leading to the BW track does not lead to dramatic changes in the initial periods, and that a bifurcation *locus* can be calculated quite accurately. Work in progress devoted to the whole population of 'redbacks', wide binaries and BW millisecond pulsar systems (Roberts 2013) is underway and will be published elsewhere.

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