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Exploring the formation of "Black Widows"

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ABSTRACT

Black Widows (BWs) are a class of binary millisecond pulsars orbiting together with very low mass donor stars ($\lesssim 10^{-2}\ M_{\odot}$). After the discovery of eclipses in the first known BW, PSR 1957+20, they are considered as close binary systems (CBSs) in which the donor star is being evaporated by the radiation emitted by the pulsar.

Standard CBS evolution calculations (i.e., without evaporation) have faced serious difficulties when trying to find ways to form BWs. When the donor star is in Roche Lobe OverFlow conditions after becoming semi-degenerate, it will evolve to longer orbital periods as consequence of its swelling reaction to mass loss. In order to reach orbital periods in the range observed for several BWs, it would need to spend times far in excess of the age of the Universe.

Here we extend the calculations presented in our previous papers on the topic, including evaporation, showing that the evolution of CBSs with a neutron star component together with an intermediate-mass, normal star provides a successful and natural scenario to account for the existence and properties of BWs.

Key words: pulsars: general — pulsars: individual (PSR J1311-3430, PSR J1719-1438, PSR 1957+20) — stars: evolution — binaries: close

1 INTRODUCTION

More than twenty years ago, Fruchter, Stinebring, & Taylor (1988) discovered an extraordinary binary pulsar: PSR 1957+20. This is the first known object of this class that exhibits eclipses. Thus, the orbital inclination of this system is nearly 90°, which allowed the evaluation of the companion mass from the mass function of the system. Considering a "canonical" pulsar (neutron star, hereafter NS) mass M_{NS} of 1.4 $M_{\odot}$, the mass of the companion M_2 was found to be of only $\approx$ 0.02 $M_{\odot}$ (or about 20 Jupiter masses; more recently, van Kerkwijk, Breton, & Kulkarni (2011) have claimed that both stars should be appreciably more massive, see below). When PSR 1957+20 was detected, the value of M_2 was considered as quite unusual, since it is huge compared to the mass of a planet[1], but much smaller than the value of 0.08 $M_{\odot}$, which represents the lower mass limit for a solar composition star completely fuelled by nuclear reactions. In addition, the characteristic of the spectacular eclipses of PSR 1957+20 led to think that a strong wind was sweeping the surface of the pulsar companion. Immediately, Phinney et al. (1988) proposed that the latter is strongly ablated by the pulsar radiation, which "evaporates" it leading to very low mass values. Moreover, this may eventually lead to the complete evaporation giving rise to isolated millisecond pulsars (MSPs, e.g., PSR 1937+214)[2]. This class of systems is currently known as "black widows" (BWs).

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[1] The first extra solar planet was discovered four years later (Wolszczan & Frail 1992) orbiting around the pulsar PSR B1257+12. At present we know four planets orbiting around it (Konacki & Wolszczan 2003).
[2] In spite of substantial work on the subject, there is still a discrepancy between the number of isolated MSPs and their progenitors predicted by the close binary evolutionary models (Pfahl, Rappaport, & Podsiadlowski 2003).

Since the discovery of PSR 1957+20 many authors have proposed evolutionary scenarios to account for the origin of BWs. These are essentially Low Mass X-Ray Binaries (LMXBs), consisting of a NS accreting matter from its low mass, normal companion. Ruderman et al. (1989) suggested an evaporation mechanism capable of reducing the mass of the companion due to wind resulting from X- and γ-ray illumination. Based on the fact that BWs are more abundant in globular clusters that in the Galactic field, King, Davies, & Beer (2003) suggested that the formation of BWs requires two stages: a binary companion is needed to spin-up the NS to become a MSP reaching the MSP-white dwarf (WD) state on a wide, loosely bound orbit. Then, by tidal interactions the WD is transformed into a semi-degenerate star in a close orbit. The further evolution would lead the system to a BW stage. For field BWs, King, Davies, & Beer (2003) required the ejection of the system from a globular cluster. Later, King et al. (2005) discussed the possibility that the companion of a given BW be the same that spun-up the NS. They judged this possibility as unlikely, unless the donor star can contract inside its Roche lobe, and achieve a sufficiently short orbital period P_{orb} in a reasonable time. As we shall see below, it is in fact possible to account for the phenomenology of BWs without invoking any stellar exchange but as a consequence of the evolution of a CBS with a suitable initial configuration.

In the framework of standard CBS evolution, if the initial P_{orb} is short enough, calculations predict that the configuration reaches a minimum period when the star becomes semi-degenerate (Savonije, de Kool, & van den Heuvel 1986). from this point on, evolution is governed by angular momentum losses due to gravitational radiation and magnetic braking. Due to its semi-degeneracy, the star *inflates* as a consequence of further mass loss. As the donor star has the size of its Roche lobe, it has to evolve to longer P_{orb}. However, in order to reach P_{orb} values compatible with those observed for BWs, it would need a time far in excess of the age of the Universe (for a detailed study of this situation see, e.g., De Vito & Benvenuto 2012). Moreover, in the standard theory the donor star transfers mass in a continuous way and does not detach. However, BWs are detached binaries. Therefore it is clear that models are incomplete and lack of some key physical ingredients. At least two phenomena, not included in the standard calculations, should be relevant in this context: the irradiation of the donor star and its subsequent evaporation due to the pulsar irradiation.

As the donor star transfers material, the latter falls onto the NS with very high velocities, giving rise to the emission of X-rays that illuminate back the donor star. The illuminated outer layers change their structure due to the incident radiation, while non-irradiated layers remain almost unchanged. This irradiation feedback may, in some cases, lead to the occurrence of unstable mass transfer in which the donor star transfers mass and detaches in a cyclic way. Thus, irradiation is important on timescales appreciably shorter than those of the evolution of the binary pair. While irradiation feedback should be a key ingredient in determining the theoretical expectation for the population of different kinds of binary systems, in Benvenuto, De Vito, & Horvath (2012) (BDVHa) and Benvenuto, De Vito, & Horvath (2014a) we have found strong indications that the advanced evolution of these systems leading to the formation of BWs is hardly affected by irradiation. As we are here mainly interested in BW systems, in this paper we shall not consider irradiation feedback of the donor star.

On the other hand, evaporation due to pulsar wind is important in determining the M_2 and P_{orb} for advanced evolutionary stages. Evaporation makes the orbit to open, allowing the system to reach longer P_{orb} values which are otherwise unreachable in the framework of the standard binary evolution treatment.

Two relevant BWs to test these ideas are PSR J1719-1438 and PSR J1311-3430. PSR J1719-1438 is a 5.7 ms MSP in orbit (P_{orb} = 132 min) with a very low mass companion recently detected by Bailes et al. (2011). In order to fit inside its Roche lobe, the companion star must have an average density $\bar{\rho} \geqslant 23\ g\ cm^{-3}$. PSR J1311-3430 was discovered by gamma-ray observations (Pletsch et al. 2012). It is a 2 ms MSP, P_{orb} = 93 min orbit. Remarkably, spectroscopic observations of the donor star (Romani et al. 2012) revealed that the donor star has a very low to complete absence of hydrogen at its surface ($X_s \leqslant 2.5 \times 10^{-5}$, where X_s is the surface abundance of hydrogen by mass).

Recently, in order to study the evolution of the above mentioned systems, we have incorporated irradiation and evaporation to our CBS stellar evolution code. We applied it to model the evolution of systems leading to the observed configurations of PSR J1719-1438 (BDVHa) and PSR J1311-3430 (Benvenuto, De Vito, & Horvath 2013) (BDVHb). Let us briefly summarize the findings of BDVHa,b. Perhaps, the main result of these papers is that the structure of PSR J1719-1438 and PSR J1311-3430 binary systems can be considered as a natural consequence of the evolution of a "canonical" mass NS orbiting a normal, zero age main sequence star of, say, 2 $M_\odot$. Depending on the initial value of the orbital period, $(P_{orb})_0$, it is possible to evolve to very different configurations: If $(P_{orb})_0$ is short enough[3] ($\approx$ 0.8 d), when the first Roche lobe overflow (RLOF) occurs, the central temperature of the donor star starts to decrease, slowing down nuclear reactions and preventing core hydrogen exhaustion. As the evolution of the system advances, the donor star becomes completely convective and thus chemically homogeneous. In this way, when the star reaches BW conditions, it has a hydrogen rich atmosphere. For larger $(P_{orb})_0$ the onset of the RLOF occurs later and core hydrogen may be exhausted; if simultaneously the donor star losses enough material, it may reach a helium rich structure with $X_s = 0$. There is another critical value for $(P_{orb})_0$, the so called bifurcation period P_{bif} ($\approx$ 0.88 d). If $(P_{orb})_0 \leqslant P_{bif}$ the system will evolve to a BW configuration; however if $(P_{orb})_0 \gtrsim P_{bif}$, the result will be a MSP-helium WD. This scenario is attractive to account for the existence of BWs without needing to invoke any tidal exchange.

In our papers on BWs (BDVHab) we have tried to understand the general evolution of CBSs in order to account for the characteristics of individual objects (PSR J1719-1438 and PSR J1311-3430 system). Here, we

[3] Critical values for initial orbital periods given in this paragraph correspond to the case of a 2 $M_\odot$ donor star, see BDVHb

shall explore the general characteristics of binary evolution that lead to the formation of BWs. The evolution of these systems is strongly dependent on several quantities, as the orbital period, the masses of the components, and the strength of the pulsar wind that drives evaporation. In BDVHab we considered fixed values for the masses of the stars: 2 $M_{\odot}$ for the donor and 1.4 $M_{\odot}$ for the NS, and also a fixed value for $\eta_{evap} \equiv \alpha_{evap} L_{PSR} = 0.04 L_{\odot}$. We shall present in this work the full parameter space to find the initial conditions that lead the CBSs to the BW region. As a byproduct, in the specific case of PSR 1957+20, we shall show below that it is possible to account for the recently measured (van Kerkwijk, Breton, & Kulkarni 2011) quotient of masses $M_{NS}/M_2 = 69.2 \pm 0.8$ at the observed orbital period $P_{orb} = 9.17$ h.

The remainder of the paper is organized as follow: In Section 2 we describe the evolutionary code, and in particular the way we treat evaporation wind. In Section 3 we present our results, and their application to the BWs observed in the Galactic field, presenting a set of initial conditions ($(M_2)_0$ and $(P_{orb})_0$) to be satisfied by BWs progenitors. Then, in Section 4 we discuss the meaning of these results and finally, in Section 5 we give some concluding remarks.

2 THE EVOLUTIONARY CODE

The basic tool for this work is the binary stellar evolution code described in Benvenuto & De Vito (2003); De Vito & Benvenuto (2012) and BDVHa. In the case of semi-detached configurations the code employs a generalized algorithm based on the Henyey technique that computes the donor structure, mass transfer rate and orbital semi-axis a in a fully implicit way. Otherwise, the code works as a standard evolutionary code. It includes detailed and updated physical ingredients fully described in BDVHa and references therein. We consider that the NS is able to accrete a fraction β of the material coming from the donor star $\dot{M}_{\rm NS} = -\beta \dot{M}_2$ (where $\dot{M}_2$ is the mass transfer rate from the donor star). As usual, we consider the Eddington mass accretion rate $\dot{M}_{Edd} = 2 \times 10^{-8}\ M_{\odot}/y$ as an absolute upper limit. We have considered that β remains constant throughout all the Roche lobe overflow (RLOF) episodes, in particular we have set $\beta = 0.5$. Also, as usual, we assumed that material lost from the binary systems carries away the specific angular momentum of the compact object ($\alpha = 1$).

As done in BDVHa, we have considered the effect of the evaporating wind driven by the pulsar radiation following the treatment given by Stevens, Rees, & Podsiadlowski (1992). In a CBS, the spin-down luminosity of the pulsar irradiates the companion. This radiation affects its radius and the orbital separation causing an extra mass loss from the donor star ($\dot{M}_{2,evap}$), independent of that due to RLOF. In this model, the mass loss driven by pulsar irradiation is given by

$$\dot{M}_{2,evap} = -\frac{\alpha_{evap}}{2 v_{2,esc}^2} L_{\rm PSR} \left(\frac{R_2}{a} \right)^2, \qquad (1)$$

where the pulsar's spin down luminosity $L_{\rm PSR}$ is given by

$$L_{\rm PSR} = 4\pi^2 I_{\rm NS} \frac{\dot{P}_{\rm NS}}{P_{\rm NS}^3} = 0.10227 \left(\frac{I_{\rm NS}}{10^{45}\ g\ cm^2} \right) \left(\frac{\dot{P}_{\rm NS}}{10^{-20}\ s/s} \right) \times \left(\frac{P_{\rm NS}}{10\ ms} \right)^{-3} L_{\odot}. \qquad (2)$$

$I_{\rm NS}$ is the moment of inertia of the NS, $P_{\rm NS}$ is its spin period and $\dot{P}_{\rm NS}$ its spin-down rate, $v_{2,esc}$ is the escape velocity from the donor star surface and α_{evap} is an efficiency factor. Notice that the relevant parameter is just the product $\eta_{evap} \equiv \alpha_{evap}\ L_{\rm PSR}$.

As discussed above, although we shall deal with systems with very short orbital periods, in this paper we do not consider the effect of the irradiation feedback of the pulsar because this effect does not sensibly affect the long term evolution of BW binaries we are addressing here.

As discussed in BDVHa, regarding radiative opacities and for temperatures $T \geqslant 10^4$ K we have employed OPAL opacities (Iglesias & Rogers 1996) while for the lower values we considered molecular opacities computed by (Ferguson et al. 2005). In both sets of tabulations, after fixing the chemical composition of the plasma, the value of the Rosseland opacity κ_R is given as a function of temperature and $R \equiv \rho/T_6^3$, where ρ is the density of the plasma and T_6 is the temperature given in million of Kelvins. The range of the tabulation is $-8 \leqslant \log R \leqslant 1$. Unfortunately, during the evolution leading to BW, the structure of the donor star becomes relatively dense and cool, reaching values of $R > 10$. This fact forces us to adopt some strategy to estimate κ_R in such conditions. Regardless the way we do it, this introduces some uncertainty in the calculations. Here and in our previous papers on BWs we have assumed that if $R > 10$ then $\kappa_R(T, R) = \kappa_R(T, 10)$. For some of the considered CBSs we have computed their evolution performing a linear extrapolation of the logarithm of opacity as a function of the logarithm of R at constant temperature. The results are hardly distinguishable from those found by imposing an upper limit for R when computing opacities.

3 CALCULATIONS AND RESULTS

We computed the evolution of CBSs, choosing initial parameters in order to reach BWs conditions. Specifically, we consider solar composition donor stars with initial mass values $(M_2)_0 = 1.5, 2.0, 2.5$, and $3.0\ M_{\odot}$. The initial mass of the NS has been set to the "canonical value" of $(M_{NS})_0 = 1.4\ M_{\odot}$. With respect to the initial orbital periods, $(P_{orb})_0$, we are interested in systems that reach appreciably shorter orbital periods. Thus, we consider values of $(P_{orb})_0$ from 0.5 d with steps of $\Delta(P_{orb})_0 = 0.05$ d up to the corresponding P_{bif} value. For each initial condition ($(M_2)_0$, $(P_{orb})_0$) we considered four values for the evaporation wind efficiency times the pulsar braking luminosity, $\eta_{evap} = 0.00, 0.04, 0.2, 1.0\ L_{\odot}$. (see Eq. 1). Taking into account the results of BDVHa, we consider that evaporation begins to operate when the CBS reaches its minimum orbital period onwards. Several of the considered systems evolve to open orbits. For these cases, we stop the calculations when $P_{orb} \geqslant 1.5$ d. We shall not obtain important qualitative changes in the overall evolution of these systems unless the onset of the evaporation occurs at a very different stage.

In Fig. 1 we present the orbital period-mass relation for a handful of the systems (as a representative of all calculations) evolved in this paper, corresponding to the case of $(P_{orb})_0 = 0.75$ d. Panels A, B, C, and D depict the evolution of systems with $(M_2)_0 = 1.5, 2.0, 2.5$, and 3.0 $M_\odot$ respectively. For the sake of reference, we included the value of the observed orbital periods of PSR J1311-3430, PSR J1719-1438, and PSR B1957+20 with horizontal dashed lines. For $(M_2)_0 = 1.5\ M_\odot$, panel A of Fig. 1 shows that for the considered efficiency values η_{evap}, the orbital period reaches values compatible with the case of PSR B1957+20 only, although M_2 is too high to be considered as a suitable solution. In contrast, for the case of larger initial donor masses, Panels B, C, and D show that masses and orbital periods are indeed compatible with BWs systems. In the cases of $\eta_{evap} = 0.0$, the model of Panel C reach the observed value of the orbital period of PSR J1311-3430 at an age of ~ 8 Gyr, for a value somewhat larger, $M_2 \sim 0.012\ M_\odot$, of that estimated for this object which is of $M_2 \sim 0.008\ M_\odot$. This mass value is reached at an age of ~ 13.6 Gyr, essentially the current value for the age of the universe. The model of Panel D never attains a mass value as low as $0.008\ M_\odot$, and the median mass value (for an inclination orbital angle of 60^o) of $\sim 0.009\ M_\odot$ is attained at an age of 14.8 Gyr, far too long to account for the system. For the case of PSR J1719-1438, the estimated mass of the companion is low as $\sim 0.001\ M_\odot$, not reached for any of these models. This analysis indicates that models in which evaporation effect is not considered are *not* appropriate to describe the evolution of BWs systems. The case of Panel B for $\eta_{evap} = 0.0$ could be an exception: this model attains the observed mass and the estimates value of the minimum mass of the companion of PSR J1311-3430 at an age of ~ 12 Gyr. However, the model fails to satisfy the condition on the mean density (see below).

The inclusion of evaporation in the models has very remarkable consequences. First, it removes angular momentum from the system, making the orbit to evolve to longer periods. Depending on the adopted value for the parameter η_{evap} it is possible to account for the orbital period of the three BW systems quoted above. Not surprisingly, with a more efficient evaporation, the systems will attain large orbital periods faster. Remarkably, increasing the value of $(M_2)_0$ not only shortens the evolutionary time scales, but also makes the relation in the plane donor mass-orbital period to become progressively less dependent of the value adopted for η_{evap}.

Donor stars must fit inside their corresponding Roche lobes. Let us define $\bar{\rho}$ as the mean density of the donor star and ρ_{lobe} as the mean density of the star if it just fills its lobe, which as a function of the orbital period, is

$$\rho_{lobe} = 0.19159 \left(\frac{P_{orb}}{1 \text{ day}} \right)^{-2} g\ cm^{-3}. \tag{3}$$

Then, the condition

$$\bar{\rho} \geqslant \rho_{lobe} \tag{4}$$

must be satisfied. The value of $\bar{\rho}$ is relevant for considering a stellar model as an acceptable solution for a particular object.

Fig. 2 show the evolution of the mean density $\bar{\rho}$ of the donor stars for the same sequences shown in Fig. 1. If we analyze the case of $(M_2)_0 = 1.5$ M$_\odot$ depicted here in Panel A together with the results presented in Fig. 1, we conclude that (in spite that the condition given by Eq. 4 is fulfilled) it does not lead to BW configurations; not only when the evaporation wind from the pulsar is neglected, but for any value of η_{evap} considered here. In the cases of $\eta_{evap} = 0$, the evolution of the mean density in Panel B helps us to conclude that the model without evaporation does not evolve to conditions appropriate to account for the configuration of the PSR J1311-3430 system.

For the other initial mass values of the donor star, and considering non zero values of η_{evap}, we find models that fulfil the criterion given in Eq. (4) for the three BW systems quoted above.

We should remark that the results presented in this paper correspond to the case in which irradiation feedback has been neglected. Notice that if irradiation is considered, mass transfer does not behave smoothly, but instead cyclic mass transfer occurs. This has been first computed by Büning & Ritter (2004) and in BDVHa for the case of BWs. This instability happens when the donor star has a mass of $\gtrsim 0.1 M_\odot$ but it is no longer present for more advanced stages of evolution such as the ones discussed in the preceding paragraph. Thus, irradiation feedback does not affect the evolutionary stages we are exploring in this work; and its neglection is justified.

Recent measurements of PSR 1957+20 (van Kerkwijk, Breton, & Kulkarni 2011) indicate a mass ratio value $q \equiv M_{NS}/M_2 = 69.2 \pm 0.8$. In order to investigate the suitability of our models to account for the PSR 1957+20 system, we show in Fig. 3 the value of q as a function of the orbital period for the strongest irradiation conditions considered in this paper ($\eta_{evap} = 1.0\ L_\odot$). We find that among the computed models there are few of them with initial masses $(M_2)_0 = 2.0$ and 2.5 $M_\odot$ for which, for the observed orbital period yield the correct mass ratio. On the other hand, for the cases of $(M_2)_0 = 1.5$ and 3.0 $M_\odot$ no suitable solution is found. In any case, we would like to state that it is not our aim to perform here a complete model for PSR 1957+20, but just to show that evaporating models are promising in this sense. We plan to address this difficult problem in a future publication.

In Table 1 we list the 17 BWs detected to date in the Galactic field from the data base available at A. Patruno's catalogue[4].

In Figure 4 we present the place of the companions for these pulsars in the $M_2 - P_{orb}$ plane. There we include the evolutionary tracks for each value η_{evap} and $(M_2)_0$, only for the extreme values of $(P_{orb})_0$. This Figure demonstrates that our models with evaporation cover the entire region occupied by the BWs of the Galactic plane. Let us remark that these models naturally account for the evolution of BWs systems. In fact, in our framework is not necessary to invoke any exchange of stars since the donor is able to spin the pulsar up on an appropriate timescale (See Section 1).

From our calculations and with the help of Figure 4 we

[4] `www.apatruno.wordpress.com/about/millisecond-pulsar-catalogue/`

Table 1. The black widows in the Galactic field listed in A. Patruno's catalogue[4]

Name	$P_{\rm NS}$ [ms]	$\dot{P}_{\rm NS}$ [10^{-20} s/s]	P_{orb} [d]	Minimum M_2 [10^{-2} $M_\odot$]
B1957+20	1.60740	1.68515	0.38197	2.142
J1810+17	1.66	⋯	0.15	4.4
J1301+0833	1.84	⋯	0.27	2.4
J1544+4937	2.15929	0.2933	0.12077	1.697
J2241-5236	2.18670	0.664	0.14567	1.172
J1446-4701	2.19470	0.98102	0.27767	1.899
J2256-1023	2.29	⋯	0.21	3.4
J1731-1847	2.34456	2.49	0.31113	3.327
J1124-36	2.4	⋯	0.225	2.7
J1311-3430	2.56037	2.0964	0.06512	0.821
J1745+1017	2.65213	0.2729	0.73024	1.369
J0023+09	3.05	⋯	0.14	1.6
J2214+3000	3.11923	1.40	0.41663	1.333
J2234+0944	3.63	⋯	0.420	1.6
J0610-2100	3.86132	1.235	0.28602	2.140
J2047+1053	4.29	⋯	0.12	3.5
J2051-0827	4.50864	1.2737	0.09911	2.666

can depict the necessary initial conditions ($(M_2)_0$, $(P_{orb})_0$) that lead to the formation of BWs in the Galactic plane. This result could be of interest to perform future population synthesis calculations or to compute the expected rates for the formation of this type of systems.

The initial conditions that a binary system have to fulfil in order to lead to the formation of BW systems are depicted in Figure 5. There we show the region of BW progenitors for different values of η_{evap}. We stress again that models without evaporation do not lead to the formation of systems with BWs characteristics in appropriate time scales in any case and so, this case is not present in Figure 5.

4 DISCUSSION

The results presented in the previous section indicate that the scenario in which a normal, intermediate mass donor star evolving together with a NS provides viable astrophysical conditions for the formation of BWs. Here we have extended the studies presented in BDVHab. In these papers we considered one value for $\eta_{evap} = 0.04\ L_\odot$. Here we allowed for the occurrence of higher evaporation rates, finding that the BW state is reached sooner for stronger evaporation rates, as expected. Also, the orbital evolution becomes markedly faster. In any case, evaporation seems to be an unavoidable ingredient of binary evolution studies if we want to reach periods in the range of a fraction of a day with donor masses M_2 of $\approx 0.01\ M_\odot$.

The results presented in this paper suggest that BWs may represent an evolutionary stage immediately previous to an isolated MSP. It is now widely accepted that, to spin NSs up to the millisecond regime, it is necessary to accrete some matter coming from a companion star. This feature is naturally provided by a configuration of the kind considered here. Later on, for the cases discussed in the text, the pulsar begins to sweep the donor star and the system becomes a BW. Since then onwards, the orbit widens becoming more and more loosely bound while the donor star is still losing mass at a non-negligible rate (say $\dot{M}_2 \approx 10^{-11} M_\odot/y$). Consequently, the system will be more fragile from a dynamical point of view, being easier to unbind by an external perturbation. In this way, the occurrence of isolated MSPs may be favored in the case of objects with a high spindown luminosity $L_{\rm PSR}$ to enhance donor evaporation.

To check whether this expectation is tenable, we have employed the ATNF[5] data base (Manchester et al. 2005) to investigate the characteristics of the MSPs that have the highest $L_{\rm PSR}$ values (see Eq. 2). Here we have ignored the cases of objects for which $\dot{P}$ is still unavailable. These objects are listed in Table 2.

The three higher (and five out of a dozen) values of $L_{\rm PSR}$ correspond to isolated MSPs whereas the others are in binaries. For the rest of MSPs with $L_{\rm PSR} > 0$ listed in the ATNF data base, 123 objects, 30 are isolated. Let us compare the fraction of all isolated MSPs with those listed in Table 2. The total fraction of isolated MSPs is of 35/135 (26%), while for those with the highest $L_{\rm PSR}$ is of 5/12 (42%). This fact suggests that high $L_{\rm PSR}$ may favour the disruption of BW binaries leading to isolated MSPs.

It is clear that wind ablation favours the widening of the orbits, making them more loosely bound. However, to unbind the binaries some other process must occur. Usually, this process has been assumed to be a deep dynamical collision. A word of caution is in order here. In spite that evaporation leads to wider orbits and makes easier to disrupt binaries, such a dynamical event has a very small probability if the system resides is in the Galactic plane (of course, close to the core of a globular cluster a disruptive collisions would be far more probable). In our Galactic neighbourhood, the Solar System has survived for 4.5 Gyr with planets moving on orbits far wider than those found here. In any case, the fact that several isolated MSPs are known in such environments indicate that evaporation may be a relevant process in reconciling theory of evolution of

[5] `http://www.atnf.csiro.au/research/pulsar/psrcat`

Table 2. The six pulsars with the highest spin down luminosity $L_{\rm PSR}$ (see Eq. 2) values among the hundred fastest pulsars with known $\dot{P}$, ordered at decreasing $L_{\rm PSR}$

Name	$P_{\rm NS}$ [ms]	$\dot{P}_{\rm NS}$ [10^{-20} s/s]	P_{orb} [d]	Minimum M_2 [$M_\odot$]	$L^*_{\rm PSR}$ [$L_\odot$]	Ref.
B1821-24A (GC)	3.05431	162.0	···	···	575.53	a
B1937+21 (F)	1.55780	10.51	···	···	281.48	b
B1820-30A (GC)	5.44000	337.50	···	···	214.40	c
J1701-3006F (GC)	2.29472	22.21	0.205487	0.02081	186.06	d
J1701-3006E (GC)	3.23373	31.03	0.158477	0.03041	92.889	d
J0218+4232 (F)	2.32309	7.738	2.028846	0.16743	62.485	e
B1957+20 (F)	1.60740	1.685	0.381966	0.02142	41.073	f
J1750-3703D (GC)	5.13994	49.28	···	···	37.115	g
B0021-72F (GC)	2.62358	6.450	···	···	36.528	h
J1740-5340A (GC)	3.65033	16.8	1.354059	0.18392	35.323	i
J1701-3006D (GC)	3.41777	12.57	1.117903	0.12152	32.200	d
J1023+0038D (F)	1.68799	1.2	0.198096	0.13465	25.517	j

* For a typical value of $I_{\rm NS} = 10^{45}\ g\ cm^2$.
a: Lyne et al. (1987); Verbiest et al. (2009)
b: Backer et al. (1982); Cognard et al. (1995)
c: Lynch et al. (2012)
d: Chandler (2003); Lynch et al. (2012)
e: Navarro et al. (1995); Hobbs et al. (2004)
f: Fruchter, Stinebring, & Taylor (1988); Arzoumanian, Fruchter, & Taylor (1994)
g: Freire et al. (2008)
h: Freire et al. (2003)
i: D'Amico et al. (2001)
j: Archibald et al. (2009)
GC: globular cluster
F: Galactic field

binary systems with the very existence of BWs and isolated MSPs. Therefore, while evaporation may be helpful, it is evident that in the models some key ingredient leading to the disruption of the binaries is still missing.

5 CONCLUSIONS

In this paper we have extended our analysis presented in Benvenuto, De Vito, & Horvath (2012) and Benvenuto, De Vito, & Horvath (2013) (BDVHab) to a wider parameter space of initial conditions.

Standard binary evolution neglecting evaporation due to pulsar irradiation has been employed to track the systems throughout their lives. There is a subtle and key interplay between orbital and structural features that must be addressed to obtain reliable results, otherwise, artificial trajectories could arise with incomplete models.

We find that, in order to reach the BW state, donor stars should have an initial mass larger than $\approx 1.5\ M_\odot$. For higher donor initial masses and considering evaporation, it is possible to account for the main observed features of BWs, including the mass quotient of PSR 1957+20.

In Benvenuto, De Vito, & Horvath (2014a) and Benvenuto, De Vito, & Horvath (2014b) we have analyzed the earlier evolution of this kind of systems fully considering irradiation feedback. The results presented there suggest that all BWs should descent from "redbacks" (systems with comparable orbital periods but much larger donor masses $\gtrsim 0.10\ M_\odot$ than BWs) while the opposite is not true. Essentially, we interpret the formation of black widows (BWs) as a natural consequence of the evolution of close binary systems with a neutron star (NS) component with suitable initial conditions and novel physical ingredients. While much work remains to be done on the study of the evolution of binary systems containing radio pulsars, models including irradiation feedback and evaporation provide an adequate framework to interpret available observations.

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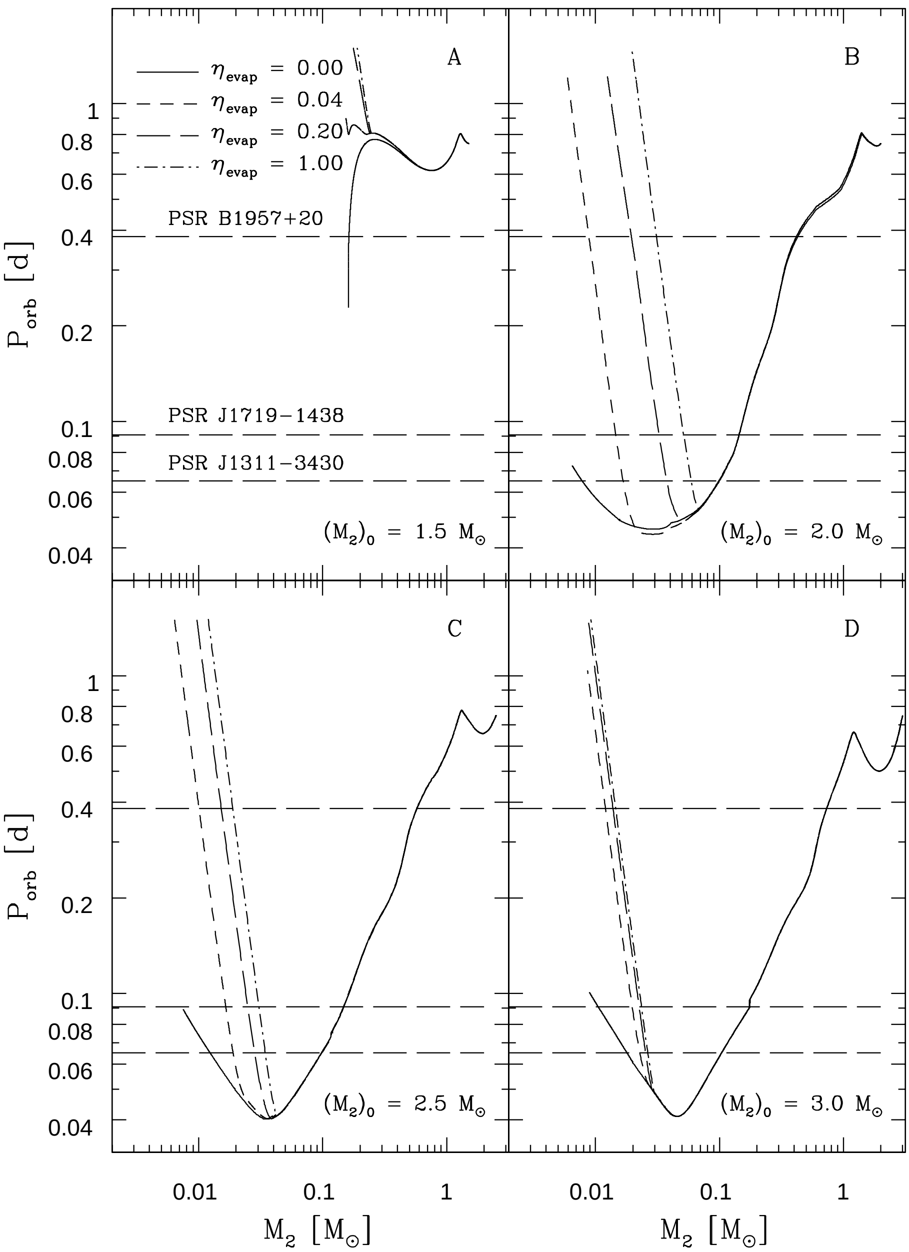

Figure 1. The orbital period-donor mass relationship corresponding to CBSs with solar composition donor stars of 1.5, 2.0, 2.5 and 3.0 $M_{\odot}$ (panels A, B, C, and D respectively) and a 1.4 $M_{\odot}$ NS, in orbit with initial period $(P_{orb})_0 = 0.75$ d . Full lines correspond to calculations neglecting evaporation wind ($\eta_{evap} = 0.0$), while short dashed, long dashed and short dashed - point lines correspond to the cases of $\eta_{evap} = 0.04, 0.2$, and 1.0 $L_{\odot}$ respectively. The observed orbital periods for PSR J1311-3430, PSR J1719-1438, and PSR B1957+20 are marked with horizontal dashed lines.

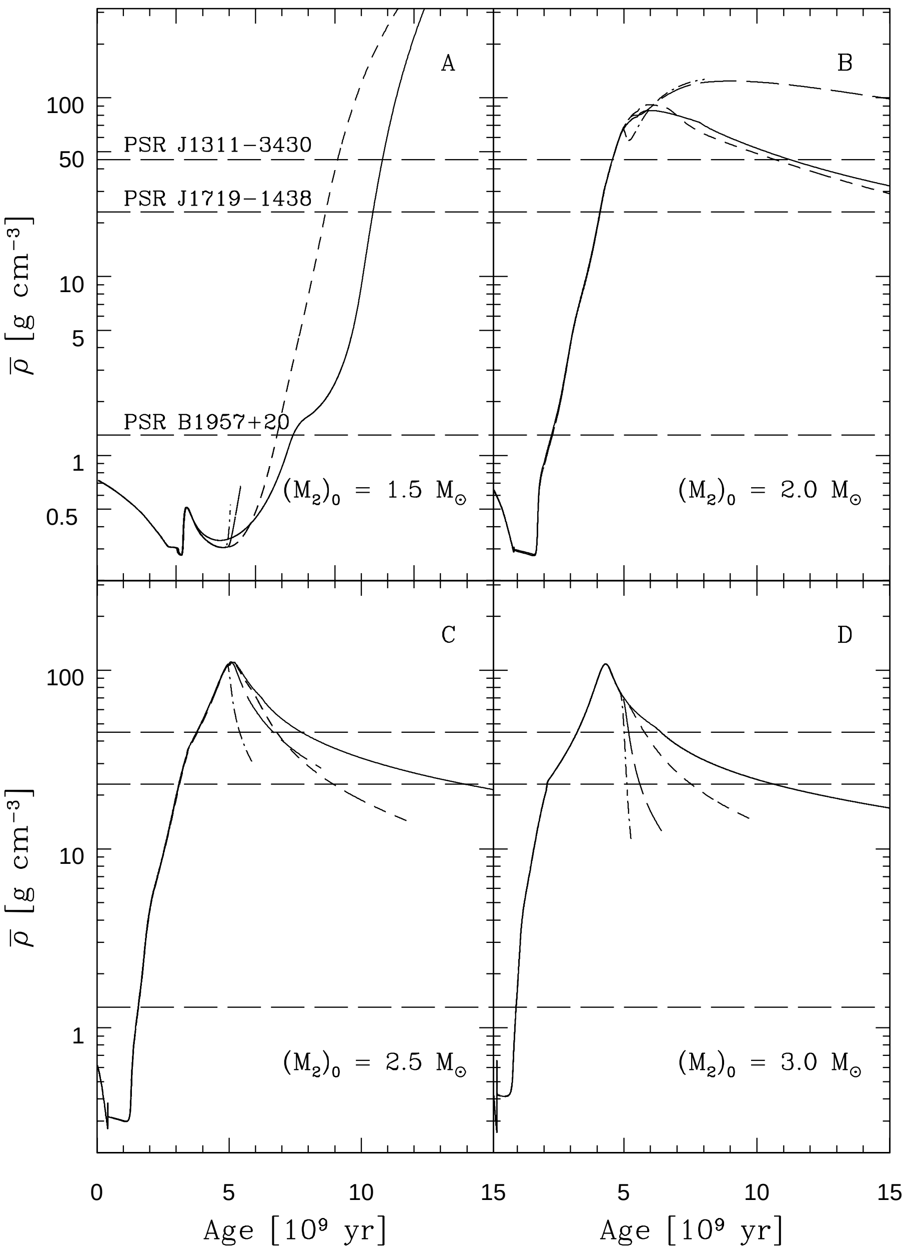

Figure 2. The evolution of the mean density $\bar{\rho}$ of the donor stars for the same sequences shown in Fig. 1. Lines and panels have the same meaning as there. Horizontal lines denote the minimum $\bar{\rho}$ (Eq. 4) for PSR J1311-3430, PSR J1719-1438, and PSR B1957+20 inferred from observations.

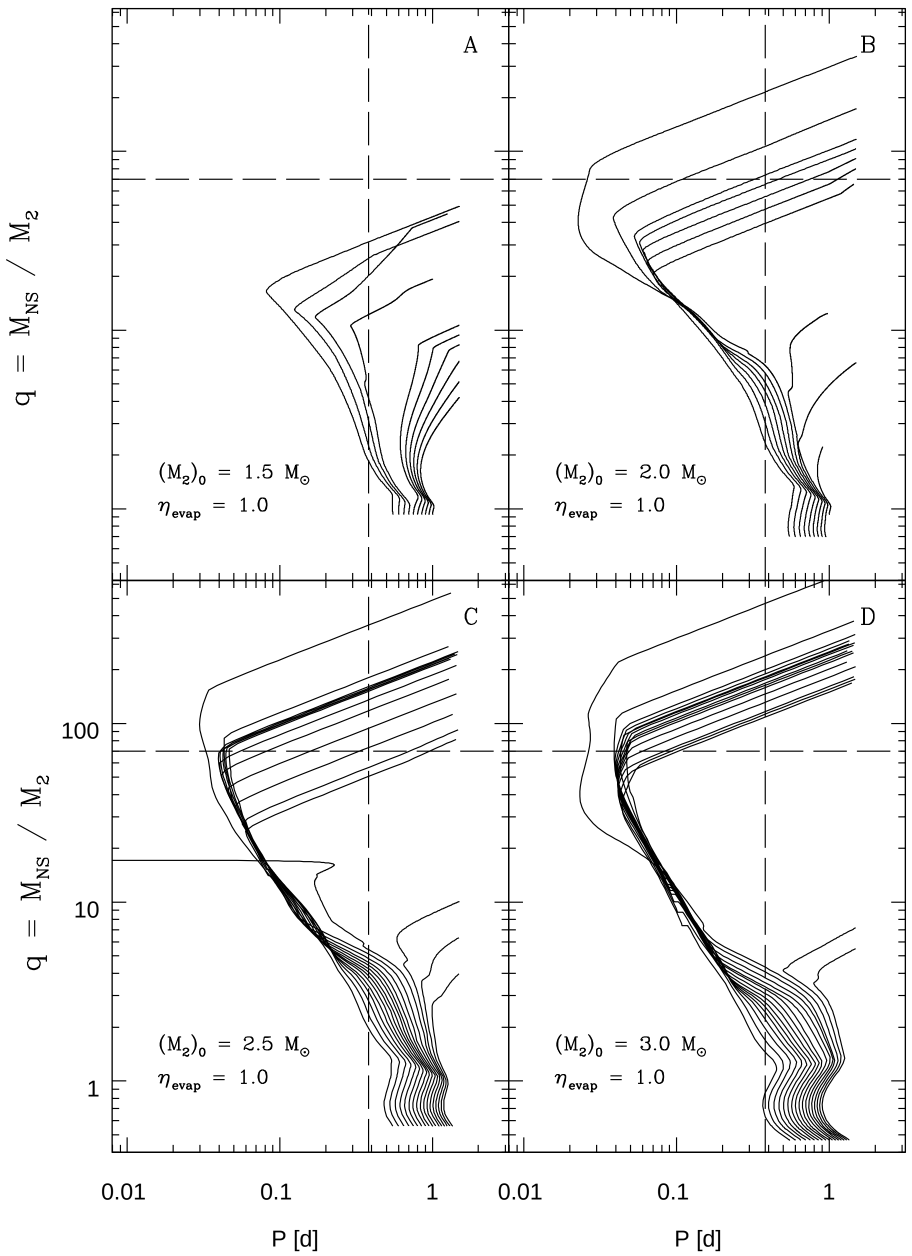

Figure 3. The evolution of the mass ratio as a function of the orbital period for the strongest irradiation conditions considered in this paper. Solid lines represent the behaviour of the models for all the initial period values, whereas with dash dot lines we denote the mass ratio and the orbital period (horizontal and vertical respectively) observed in PSR 1957+20.

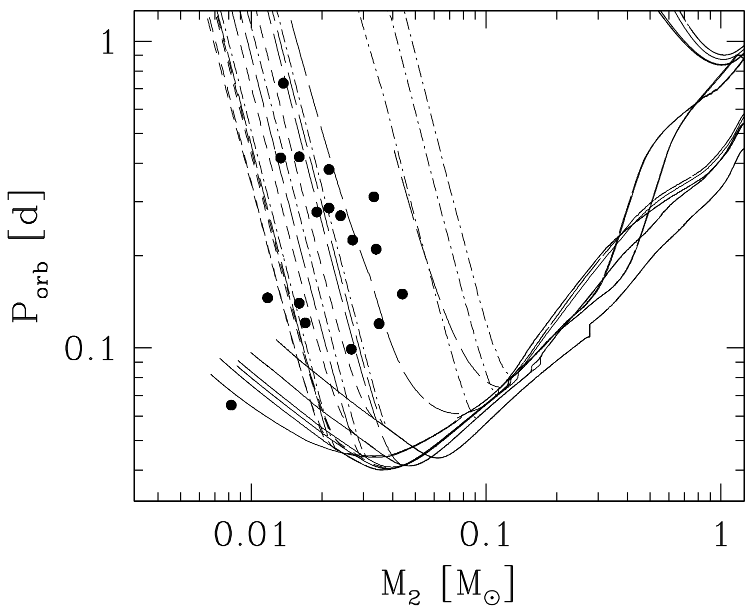

Figure 4. The $M_2 - P_{orb}$ plane region corresponding to BWs. We plot the tracks corresponding to the four values of initial donor masses considered in this paper ($(M_2)_0 = 1.5, 2.0, 2.5$ and 3.0 $M_\odot$) for the lowest and highest initial orbital period values ($(P_{orb})_0 = 0.55$ and 1.0 d). For each case, we show with solid line the tracks where the evaporation wind is fully neglected ($\eta_{evap} = 0.0$), and with short dash line, long dash line and dot - short dash line the cases of $\eta_{evap} = 0.04, 0.20$ and 1.00 $L_\odot$ respectively. Dots denote the Galactic field BWs companions taken from A. Patruno's catalogue[4]. We remind the reader that observations provide *minimum* mass values. The evolution of CBSs considered here fully account for this observational data.

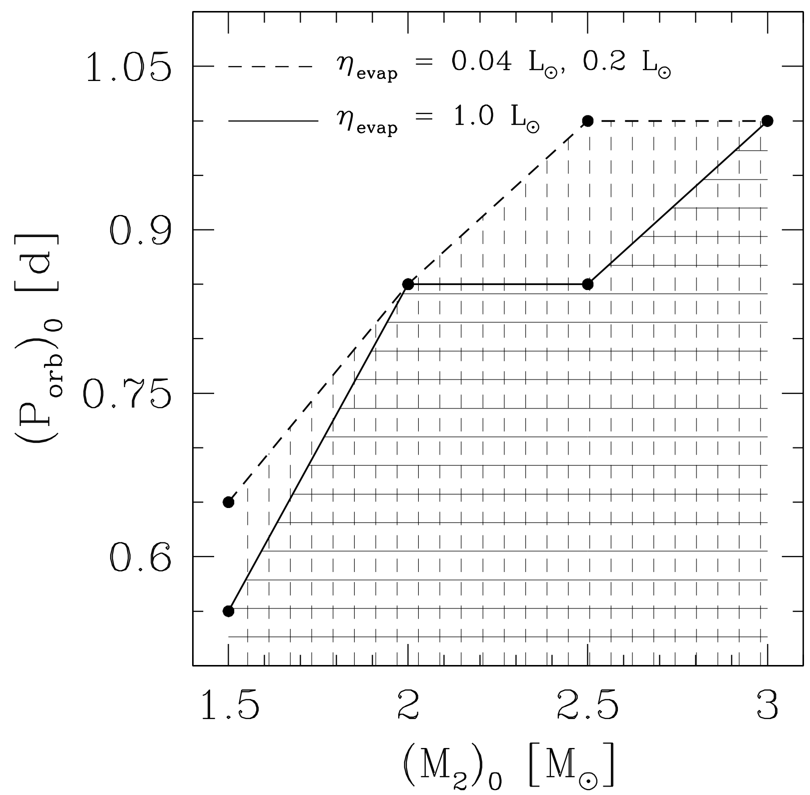

Figure 5. The region of initial conditions that lead to the formation of BW systems for each value of η_{evap} considered in this paper. Notice that, since the case $\eta_{evap} = 0.0$ does not lead to BW configurations it is not present in this Figure. Full lines indicate the case of $\eta_{evap} = 1.0\ L_\odot$ while dashed lines represent the cases of $\eta_{evap} = 0.2\ L_\odot$ and $0.04\ L_\odot$.