The Astrophysical Journal Letters, 753:L33 (4pp), 2012 July 10 doi:10.1088/2041-8205/753/2/L33

EVOLUTIONARY TRAJECTORIES OF ULTRACOMPACT “BLACK WIDOW” PULSARS WITH VERY LOW MASS COMPANIONS

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Received 2012 April 28; accepted 2012 June 5; published 2012 June 21

ABSTRACT

The existence of millisecond pulsars with planet-mass companions in close orbits is challenging from the stellar evolution point of view. We calculate in detail the evolution of binary systems self-consistently, including mass transfer, evaporation, and irradiation of the donor by X-ray feedback, demonstrating the existence of a new evolutionary path leading to short periods and compact donors as required by the observations of PSR J1719-1438. We also point out the alternative of an exotic nature of the companion planet-mass star.

Key words: pulsars: general – pulsars: individual (PSR J1719-1438) – stars: evolution

Online-only material: color figures

1. INTRODUCTION

The recent report (Bailes et al. 2011) of a binary millisecond pulsar in a 2.2 hr orbit featuring a Jupiter-like mass companion with a lower bound for the mean density of $\bar{\rho} \geqslant 23\ \mathrm{g\ cm^{-3}}$ is both important and challenging for stellar evolution theory. Indeed, the role of the pulsar wind and illumination feedback have been deemed as important (Bailes et al. 2011), but it was not clear whether the interplay of all the effects is enough to reproduce the observed features. In order to account for the existence of the PSR J1719-1438 system, we have looked for an evolutionary scenario in which a normal star evolves losing most of its mass and reaching the observed configuration (see Table 1). We have considered close binary systems composed of an accreting neutron star (NS) orbiting together with a normal donor star. We attempt to answer the full history of these systems below, and report the first complete results in this work.

2. CALCULATIONS AND RESULTS

In the case of this kind of system, the donor star evolves essentially as an isolated object up to the moment at which its radius R_2 nearly equals the radius of the Roche lobe R_L.[3] This phenomenon is usually referred to as the onset of the Roche lobe overflow (RLOF). Near RLOF, tidal dissipation forces the orbit to become circular with a period P_i, a starting point for the calculations. For the case of low-mass donor stars with masses fulfilling the condition $0 < M_2/M_1 < 0.8$, the radius of a sphere with the volume of the Roche lobe can be approximated by (Paczyński 1971)

$$R_L = 0.46224\, a \left(\frac{M_2}{M_1 + M_2} \right)^{1/3}, \tag{1}$$

where a is the semiaxis of the circular orbit. From that moment on, the donor star transfers mass across the Lagrangian point L_1 toward the NS. This process, in turn, makes the orbit evolve. At present, it is not clear how much of the matter transferred from the donor star is effectively accreted by the NS. Hereafter, we define β as the fraction of transferred material that is accreted by the NS ($\dot{M}_1 = -\beta \dot{M}_2$, but always below the Eddington limit $\dot{M}_{\mathrm{Edd}} = 2 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$; see, e.g., Podsiadlowski et al. 2002). If $\beta < 1$ some material is lost by the system carrying away the specific angular momentum of the secondary. As the value of β is not critical in determining the evolution of this kind of system (De Vito & Benvenuto 2012), hereafter we shall assume an average value of $\beta = 1/2$. This value of β has been usually assumed, for example, in Podsiadlowski et al. (2002), and more recently in population synthesis calculations by Belczynski et al. (2008). Also, gravitational radiation (Landau & Lifshitz 1975) and magnetic braking (Verbunt & Zwaan 1981) are known to provide relevant angular momentum sinks.[4]

$\dot{M}_2$ due to RLOF is described by the expression given by Ritter (1988),

$$\dot{M}_{2,\mathrm{RLOF}} = -\dot{M}_0 \exp\left(\frac{R_2 - R_L}{H_P} \right), \tag{2}$$

where $\dot{M}_0$ is a smooth function of M_1 and M_2, and H_P is the pressure scale height at the photosphere (for further details, see Ritter 1988). The above given description corresponds to the standard treatment for the evolution of low-mass X-ray binaries; see, e.g., Podsiadlowski et al. (2002). However, as will be clear below, these ingredients are *not* enough to account for the formation of a binary pair like PSR J1719-1438. Another effect that drives further mass loss from the donor star is the evaporating wind, driven by the pulsar radiation. Following Stevens et al. (1992), we include this effect by considering

$$\dot{M}_{2,\mathrm{evap}} = -\frac{f}{2 v_{2,\mathrm{esc}}^2} L_P \left(\frac{R_2}{a} \right)^2, \tag{3}$$

where the pulsar’s spin down luminosity L_P is given by $L_P = 4\pi^2 I_1 P_1 \dot{P}_1$ (I_1 is the moment of inertia of the NS, P_1 is its spin period, and $\dot{P}_1$ is its spin-down rate), $v_{2,\mathrm{esc}}$ is the escape

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[3] As usual, we shall refer to the NS (donor star), the primary (secondary), with subindex 1 (2).

[4] Another law of magnetic braking has been presented in Ivanova & Taam (2003); if adopted, the results of the present work may change. This will be explored in a future paper.

velocity from the donor star surface, and f is an efficiency factor that will be set to 0.1 as in Stevens et al. (1992). As we shall be concerned with very short orbital periods, a relevant phenomenon to consider is irradiation feedback. When the donor star transfers mass onto the NS, it releases an accretion luminosity that illuminates the donor star with flux $F_{\rm irr} = (\alpha_{\rm irr}/4\pi a^2)(GM_1/R_1)\dot{M}_1$, where $\alpha_{\rm irr}$ is a constant that accounts for the fact that all the luminosity neither has to be released as electromagnetic radiation, nor has to be emitted isotropically (Büning & Ritter 2004). The radiation incident onto the donor star partially blocks the release of its internal energy, modifying its evolution. This problem has been addressed by Hameury & Ritter (1997). Here we shall assume the validity of the point-source model, i.e., that the accreting NS is the only source of radiation incident onto the donor star.

In order to compute the evolution of these systems, we have employed our detailed (Henyey) evolutionary code described in Benvenuto & De Vito (2003) and De Vito & Benvenuto (2012), which has been modified to incorporate irradiation feedback and evaporating winds as described above. For a compact binary system to be an adequate candidate to account for the properties of PSR J1719-1438, it must have a very close orbit. The RLOF will occur during the hydrogen core burning stage; this is usually classified as a Class A mass transfer episode (Kippenhahn & Weigert 1967; whereas Class B and C episodes correspond to the cases in which the onset of the RLOF occurs after the exhaustion of core hydrogen and helium, respectively). An exploration of the parameter space defining a particular compact binary system (M_1, M_2, P_i) indicates that there exists a restricted region that leads to the formation of systems like PSR J1719-1438. For example, there is a narrow range for the initial orbital period: if P_i is too short (say, $<$0.5 days) even at the minimum radius (on the ZAMS), the donor star would be transferring mass. On the other side, if P_i is larger than about $\approx$0.9 days, the system evolves on an orbit that widens enough to allow for the formation of a low-mass ($\sim$0.25 $M_\odot$) helium-white-dwarf–millisecond-pulsar pair (see, e.g., De Vito & Benvenuto 2012). Thus, the values of P_i leading to objects on converging orbits is very restricted. If the formation of the PSR J1719-1438 system proceeded the way we considered here, P_i should have fallen in this interval.[5] Furthermore, as we shall see below, the system has to evolve for a quite a long time to reach mass values as low as those indicated by observations. This, in turn, imposes a lower limit for its initial mass: if it is very low, the system would need to evolve for a time in excess of the age of the universe. For more massive stars, there exists a limit imposed by the stability of the mass transfer at the onset of the RLOF (for further details see Podsiadlowski et al. 2002). This set of conditions strongly suggests that these systems should be rare.

Observations of the pulsar signal are quite stable, and thus do not suggest that PSR J1719-1438 is undergoing an RLOF episode (Bailes et al. 2011; M. Bailes 2012, private communication). Thus, the donor star should be smaller than its corresponding Roche lobe. If RLOFs were the only process giving rise to mass loss from the donor star, this fact would be very difficult to account for. It is well known that low-mass white dwarfs (WDs) behave like polytropic spheres of index $n = 1.5$. For these structures, the mass–radius relation is $R \propto M^{-1/3}$. Therefore, the star expands in response to mass loss. This behavior continues as long as the equation of state is dominated by electron degeneracy. As the star experiences further mass loss, it lowers its density and the degree of degeneracy; non-ideal effects become more important. Eventually, the mass–radius relation changes, and there is a mass value for which the radius passes through a maximum. For example, if the object has a helium-dominated composition, this corresponds to an object with a mass of $M_2 = 2 \times 10^{-3}\, M_\odot$, which has a radius of $R_2 = 5 \times 10^{-2}\, R_\odot$ (see, e.g., Deloye & Bildsten 2003). As the less massive object in the system loses mass (and angular momentum), we arrive at a situation in which the orbit gets wider while keeping $R_2 - R_L \approx H_P$. When the donor star reaches the maximum-radius mass value, further mass loss will force the star to contract, *detaching* the donor star from its Roche lobe (note that for these mass values of the donor star, the timescale of orbital evolution due to gravitational radiation is too long to lead the donor star into contact).

Table 1
Parameters of the PSR J1719-1438 Employed in the Calculations (from Bailes et al. 2011)

Parameter	Value
ν (s^{-1})	172.70704459860(3) Hz
$\dot{\nu}$ (s^{-2})	$-2.2(2) \times 10^{-16}$
Epoch (MJD)	55411.0
$P_{\rm orb}$ (days)	0.090706293(2)
$a_p \sin i$ (lt-s)	0.001819(1)
$\bar{\rho}$ (g cm^{-3}) (inferred)	$\geqslant 23$

If mass loss/transfer were only due to a RLOF episode(s), in reaching the observed configuration, the system would need a timescale in excess of the age of the universe. A natural way out of this apparent paradox is provided by the evaporating wind described above. As a matter of fact, during the advanced stages of evolution in which the donor star mass becomes very low ($M_2 \leqslant 2 \times 10^{-2}\, M_\odot$), such evaporating wind dominates the donor star mass losses and the orbital evolution, even if the system is still on RLOF conditions. This effect makes the orbit become wider than it would be if we consider RLOF solely, making the star *detach* from its Roche lobe before reaching mass values as low as that corresponding to the maximum radius for its composition. In order to explore the plausibility of this scenario, we have computed the evolution of several systems assuming a solar composition donor star with an initial mass value of $M_2 = 2\, M_\odot$, a “canonical” NS of $M_1 = 1.4\, M_\odot$, and some values for the initial orbital period that lead to this kind of binary systems: $P_i = 0.75$ days, 0.80 days, and 0.85 days. We considered evolutionary sequences with and without irradiation feedback. In this Letter, we shall not discuss the process of the formation of main-sequence–NS close binary systems (CBSs) from which we begin our calculations. Also, we should warn the reader that it is be possible to arrive at a configuration like that of PSR J1719-1438 from initial conditions different from the ones we assumed. These processes have been discussed by Belczynski & Taam (2004) and references therein. The work by van Haaften et al. (2012) noticed several problems in the formation of the system and attempted to model the outcome varying the donor and its wind.

In Figure 1, we show the orbital period of the system as a function of the donor mass. It is remarkable that irradiation feedback does not induce any dramatic effect on such a relation. The observed period for PSR J1719-1438 indicates that for each

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[5] In any case, here we should remark that the interval of P_i referred above depends on the particular physical ingredients assumed in our computations that are certainly not fully known. The related present uncertainties should affect the precise value of the period interval, although it will still be within a narrow range.

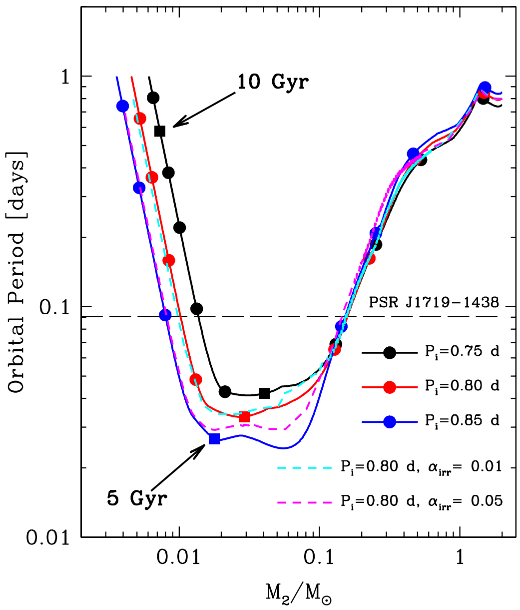

Figure 1. Orbital period–mass relation for the donor star corresponding to systems with a solar composition, $2\,M_\odot$ normal star, and a $1.4\,M_\odot$ neutron star in orbits with initial periods P_i of 0.75 days (black), 0.80 days (red), and 0.85 days (blue) from top to bottom, respectively. Full lines correspond to calculations neglecting irradiation feedback, while the results for 0.80 days and two values for the irradiation parameter $\alpha_{\rm irr} = 0.01$ and 0.05 are shown with a dashed line (cyan in the online version) and a dot-dashed line (pink in the online version), respectively. Stars spend 1 Gyr evolving leftward from one mark to the next one along the trajectories. The observed orbital period for PSR J1719-1438 is marked with a horizontal dashed line. These systems attain the observed period with adequate masses ($< 0.05\,M_\odot$) after long (6–7 Gyr) but acceptable timescales.

(A color version of this figure is available in the online journal.)

model two solutions exist: one with $M_2 \geqslant 0.10\,M_\odot$, (while the orbit is shrinking) and other with $M_2 = 0.01\,M_\odot$ (while the orbit is expanding). In view of the mass function of this system (Bailes et al. 2011),

$$f(m_c) = \frac{4\pi^2}{G}\left(\frac{a_2 \sin i}{P}\right)^2 = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2}$$
$$= 7.85(1) \times 10^{-10}\,M_\odot, \qquad (4)$$

where P is the orbital period, a_2 is the semiaxis of the pulsar orbit, and i is the inclination angle of the orbit with respect to the line of sight, it is difficult to consider the first solution as physically plausible. For $M_1 = 1.40\,M_\odot$, we would need $\sin i \approx 0.01$, which has a very low probability, whereas for the other solution we still need small but tolerable values of $\sin i \approx 0.1$. Note that because at late times the evaporating wind dominates mass loss/transfer (see below), it accelerates the evolution of the system (as compared with the standard case in which this effect is ignored), making it possible to reach a configuration compatible with the observed state of PSR J1719-1438 within a long but acceptable timescale of 6–7 Gyr. We show in Figure 2 the mass transfer rate for the case of $P_i = 0.8$ days, with and without irradiation feedback. Due to irradiation, the donor star undergoes cyclic mass transfer episodes in a way similar to that found by Büning & Ritter (2004). Note that this oscillating behavior is restricted to an intermediate stage of evolution. Despite the uncertainties associated with the present treatment of irradiation feedback (Ritter 2008), it is a fortunate situation that the final properties of the system are largely independent of the former. We show in Figure 3 the evolution of the donor and the Roche lobe radii, demonstrating that the system ultimately detaches around 6 Gyr. Finally, in Figure 4 we show the evolution of the mean density of the donor star $\bar{\rho}$. We find that from ages ≈4 Gyr onward (well before detachment from the Roche lobe), $\bar{\rho}$ overcomes the lower limit deduced from observations.

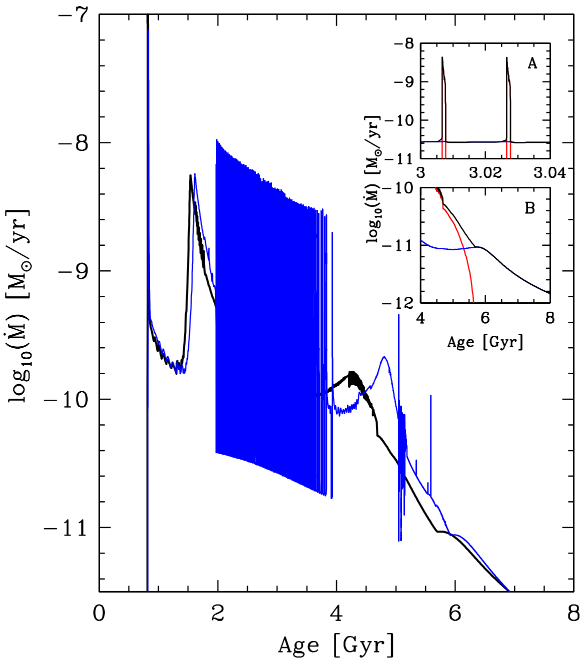

Figure 2. Evolution of the mass transfer rate from the donor star for the case $P_i = 0.8$ days, ignoring (thick line; black in the online version) and considering (thin line; blue in the online version) irradiation feedback (with $\alpha_{\rm irr} = 0.05$) as in Figure 1. The mean value of the mass transfer rate is very similar, irrespective of the inclusion of irradiation feedback. However, for ages between 2 and 4 Gyr, irradiated models undergo a sequence of RLOF episodes similar to those found by Büning & Ritter (2004). Some of these episodes are depicted in further detail in inset (A) where thick solid, and thin dashed and dotted lines (black, red, and blue lines in the online version) represent the total mass transfer rate, the RLOF, and evaporation contributions, respectively. Finally, in inset (B) we show the same quantities (with lines (colors in the online version) having the same meaning as in inset (A)) at the end of the non-irradiated sequence (irradiated ones behave in a similar way). Remarkably, after 5.5 Gyr mass transfer rate is dominated by the evaporation wind driven by pulsar irradiation.

(A color version of this figure is available in the online journal.)

Regarding the final internal composition of the donor star, it depends on the value of P_i. For the shortest possible initial orbital periods, core hydrogen burning is quenched by mass loss (internal temperature falls down fast enough to appreciably slow down nuclear activity) and the final hydrogen abundance is ≈0.45 by mass. For the largest P_i for which CBSs evolve to a black widow configuration, compatible with the characteristics of the PSR J1719-1438 system, hydrogen is almost absent, creating a helium-dominated composition. It is worth noting that for the formation path we addressed in this Letter, no other composition is possible for the donor star interior.

3. DISCUSSION AND CONCLUSIONS

The conclusion of this study is the identification of a definite new path for the evolution of binary systems evolving into planet-like–millisecond-pulsar pairs, featuring $R_2 < R_L$ for the donor star and a mean density $\bar{\rho} > 23$ g cm^{-3} for it. Our calculations show self-consistently that this is indeed possible, even for objects composed of a mixture of hydrogen and helium, without the need for postulating a carbon interior, on

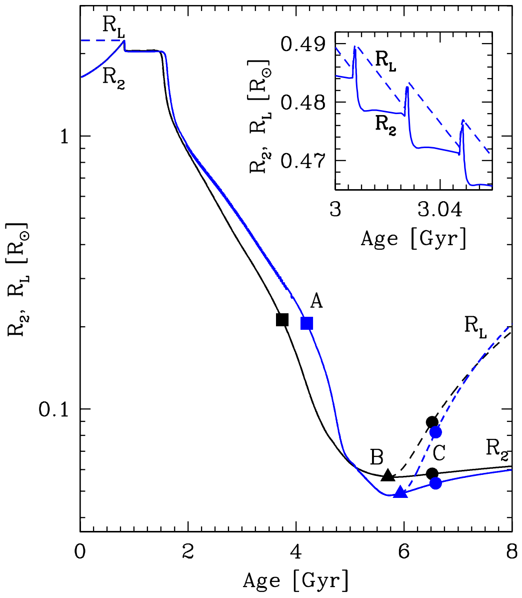

Figure 3. Evolution of the radius of the donor star R_2 (solid lines) and its corresponding Roche lobe R_L (dashed lines) for the same models of Figure 2, ignoring (thick lines (black in the online version)) and considering (thin lines (blue in the online version)) irradiation feedback (with $\alpha_{\rm irr} = 0.05$). In the case of the irradiated sequence, the donor star suffers from a series of contractions and expansions corresponding to the cyclic mass transfer regime, shown in detail in the inset. However, the long-term evolution of the radii of irradiated models is very similar to those of non-irradiated ones. Points labeled with A and C correspond to the stages at which the orbital period is equal to the observed value, while B indicates the final detachment of the donor star. Note that, remarkably, due to the evaporation wind driven by pulsar irradiation, the donor star attains the orbital period observed for PSR J1719-1438 with low-mass values ($M_2 \approx 0.010\, M_\odot$) in detached conditions, as indicated by observations.

(A color version of this figure is available in the online journal.)

a reasonable timescale. The initial conditions for this evolution are actually quite stringent, as identified above; otherwise the outcome of the evolution is very different.

Finally, the exciting possibility that the companion of the millisecond pulsar PSR J1719-1438 is *not* WD-like but a truly exotic object (i.e., composed of some form of quark matter) should not be overlooked. This would easily explain why there is no modulation even for an edge-on inclination. Actually, in the latter case, the stringent photometric limits derived in Bailes et al. (2011) using the Keck-LRIS instrument cannot be used to place constraints on the inclination because the absence of signal is a quite natural outcome. In other words, for the cases of a strange quark matter nugget or structured strangelet chunk, the size of the companion would be too small to detect any photometric signal. The exotic model also predicts that no carbon/helium lines should be ever observed associated with the companion. In addition, the lack of detection of evaporation signatures (Bailes et al. 2011) would be naturally accommodated. Finally, and because of angular momentum considerations, we expect that the orbit angular momentum $\boldsymbol{J}$ of the quark companion to be aligned with the spin of the pulsar "born in original spin" (e.g., Camilo et al. 1994). These are quite strong, albeit straightforward, predictions to be checked in future studies addressing the nature of this system. The proposals of extended exotic stars (strangelet dwarfs, Alford et al. 2012; and strange dwarfs, Glendenning et al. 1995) would need an evaluation of their surface properties, which would still depend on the existence or absence of a normal matter atmosphere to reprocess the incident pulsar radiation. This would be difficult to distinguish from conventional helium or carbon WDs. However, in these scenarios there is no link between the evolution of the system and the final masses and period, and the millisecond pulsar could be very young and not recycled at all.

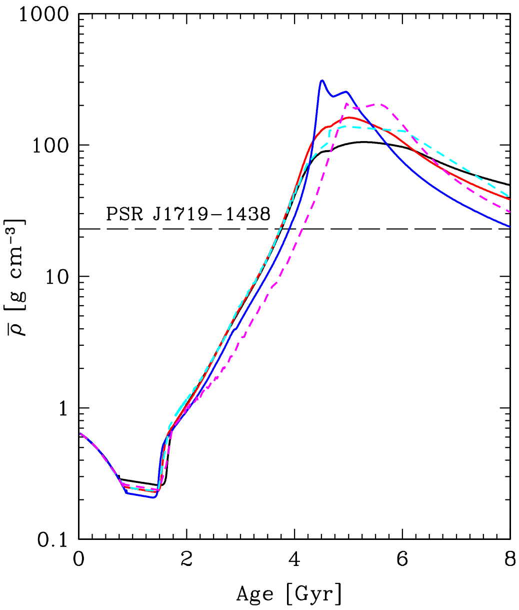

Figure 4. Evolution of the mean density for the donor star for the same sequences shown in Figure 1. The meaning of lines is explicitly indicated (colors in the online journal have the same meaning as in Figure 1). We show with a horizontal line the minimum mean density found in Bailes et al. (2011) inferred from observations. First, the systems attain the observed orbital period when under RLOF conditions, when the mean density is lower than the value $\bar\rho = 23$ g cm^{-3}. After that the star detaches from the Roche lobe and the mean density increases above the referred minimum value, in agreement with observations.

(A color version of this figure is available in the online journal.)

We thank our referee, Chris Belczynski, for his prompt and constructive report that helped us to improve the original version of this Letter. O.G.B is a member of the Carrera de Investigador of the CIC-PBA Agency and M.A.D.V. is a member of the Carrera de Investigador, CONICET, Argentina. J.E.H. has been supported by Fapesp (São Paulo, Brazil) and CNPq, Brazilian funding agencies.

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