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

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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 \( \bar{\rho} \geq 23 \text{ g cm}^{-3} \) 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 \( R_L \) nearly equals the radius of the Roche lobe \( R_L \). 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 \( P_\text{c} \), 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)

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

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 \( \beta \) as the fraction of transferred material that is accreted by the NS \( \left( M_1 = -\beta M_2, \text{ but always below the Eddington limit } M_\text{Edd} = 2 \times 10^{-9} \, M_\odot \text{ yr}^{-1} \right) \); 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 \( \beta \) 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 \( \beta \) 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.

\( M_2 \) due to RLOF is described by the expression given by Ritter (1988),

\[
\frac{dM_2}{dt} = -M_0 \exp \left( \frac{R_2 - R_L}{H_P} \right),
\]

where \( M_0 \) 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

\[
\frac{dM_2}{dt} = -f \frac{L_P}{2v_{\text{esc}}^2} \left( \frac{R_2}{a} \right)^2,
\]

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), \( v_{\text{esc}} \) is the escape speed of a material particle from the donor star.

As usual, we shall refer to the NS (donor star), the primary (secondary), with subindex 1 (2).
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 \( F_{\text{irr}} = (\rho_{\text{irr}} \times 4\pi \alpha^2)(GM_1/R_1)M_1 \), where \( \rho_{\text{irr}} \) 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 (Heneyey) 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 \((M_1, M_2, P_1)\) 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 \( P_1 \) 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 \( P_1 \) is larger than about \(\approx0.9\) days, the system evolves on an orbit that widens enough to allow for the formation of a low-mass \((\sim0.25\,M_\odot)\) helium-white-dwarf–millisecond-pulsar pair (see, e.g., De Vito & Benvenuto 2012). Thus, the values of \( P_1 \) leading to objects on converging orbits is very restricted. If the formation of the PSR J1719-1438 system proceeded the way we considered here, \( P_1 \) should have fallen in this interval. 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 \( n = 1.5 \).

\[ \frac{\alpha_{\text{irr}}}{\alpha} = \frac{0.1}{\approx 0.08} \approx 1.25 \]

In any case, here we should remark that the interval of \( P_1 \) 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.

Table 1

| Parameter | Value |
|-----------|-------|
| \( \nu (\text{c}^{-1}) \) | 172.70704459860(3) Hz |
| \( \dot{\nu} (\text{c}^{-2}) \) | \(-2.22 \times 10^{-16}\) |
| Epoch (MJD) | 55411.0 |
| \( P_{\text{orb}} \) (days) | 0.090706293(2) |
| \( a_p \sin i \) (lt-s) | 0.001819(1) |
| \( \ddot{\rho} \) (g cm\(^{-3}\)) (inferred) | \( \geq 23 \) |
model two solutions exist: one with $M_2 \geq 0.10 \, M_\odot$, (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),

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

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 Bünning & 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 $\approx 4$ Gyr onward (well before detachment from the Roche lobe), $\bar{\rho}$ overcomes the lower limit deduced from observations.

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 $\approx 0.45$ 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
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 a 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 $J$ 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.

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