Binary evolution leading to the formation of the very massive neutron star in the J0740+6620 binary system

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1 INTRODUCTION

Millisecond pulsars (MSP) are neutron stars (NS) with very short and stable spin period ($P \lesssim 30$ ms, $P \lesssim 10^{-3}$). They are widely considered as an useful tool for testing fundamental physics and studying gravitational waves emission, binary stellar evolution, and even the properties of the interstellar medium. At present we know that there are several MSPs in binary systems (Manchester, et al. 2005), most of them orbiting together with another NS or with a white dwarf (WD). If the orbit of the system is nearly edge on, the mass of the NS and its companion can be inferred with high precision by radio timing observations, with the measurement of the relativistic Shapiro delay (Shapiro 1964). Knowing the NS mass is critical for understanding the interior of these stars, since the mass provides a strong constraint in the equation of state of matter (known as the Tolman, Oppenheimer and Volko

ABSTRACT

We study the evolution of close binary systems in order to account for the existence of the recently observed binary system containing the most massive millisecond pulsar ever detected, PSR J0740+6620, and its ultra-cool helium white dwarf companion. In order to find a progenitor for this object we compute the evolution of several binary systems composed by a neutron star and a normal donor star employing our stellar code. We assume conservative mass transfer. We also explore the effects of irradiation feedback on the system. We find that irradiated models also provide adequate models for the millisecond pulsar and its companion, so both irradiated and non irradiated systems are good progenitors for PSR J0740+6620. Finally, we obtain a binary system that evolves and accounts for the observational data of the system composed by PSR J0740+6620 (i.e. orbital period, mass, effective temperature and inferred metallicity of the companion, and mass of the neutron star) in a time scale smaller than the age of the Universe. In order to reach an effective temperature as low as observed, the donor star should have an helium envelope as demanded by observations.

Key words: (stars:) binaries (including multiple): close, (stars:) pulsars: general
2.14$^{+0.10}_{-0.08}$ $M_\odot$ against gravitational collapse (see, for example, Fig. 2 of Lattimer & Prakash 2004). So, the very existence of a NS as massive as that present in PSR J0740+6620 is sufficient to discard them as unrealistic.

On the other side, it is interesting to find the way the system PSR J0740+6620 could have been formed. This is the goal of the present paper. For this purpose, we study the evolution of a set of close binary systems composed by a normal, non degenerate star together with a NS\(^{3}\) that accretes mass from its companion. The companion acts as a donor star, and eventually evolves into a WD. This is a standard scenario explored by several authors as, e.g., Podsiadlowski, Rappaport & Pfahl (2002), Benvenuto & De Vito (2005), and Tailo, et al. (2018). The NS becomes a MSP as a result of the increase of its mass and angular momentum due to mass transfer from its companion (Alpar, et al. 1982). This standard scenario predicts a long and stable episode of mass transfer as a consequence of the nuclear evolution of the donor star and angular momentum losses, and a small number of RLOFs due to thermonuclear flashes (Benvenuto & De Vito 2005).

Pfahl, Rappaport & Podsiadlowski (2003) first performed a study that combines binary population synthesis in the Galactic disk and detailed evolutionary calculations of low - and intermediate-mass X-ray binaries (LMXBs). In their comprehensive work, the authors computed distributions of the orbital periods, donor masses, mass accretion rates of LMXBs, and orbital-period distributions of binary MSPs. In particular, they studied the distribution of NS masses resulting from close binary evolution. Their calculations lead to the formation of NSs as massive as $\sim 2.5 M_\odot$.

Employing the MESA code, Lin, et al. (2011) computed an extensive grid of binary evolutionary tracks with initial donor masses in the range of $1 \sim 4 \ M_\odot$ and initial orbital periods between 10 and 250 h. Of particular interest is their Figure 4, where it is shown that NS masses greater than $2 \ M_\odot$ are possible for systems with the low mass companions ($\sim 0.15 \sim 0.25 \ M_\odot$), and orbital periods between 10 and 80 h. They applied their results to PSR J1614-2230, which has a $1.97 \pm 0.04 \ M_\odot$ NS (Demorest, et al. 2010), an orbital period of 8.7 days, and a companion star of $0.5 \ M_\odot$. The authors claim that an initial $1.4 \ M_\odot$ NS together with a $3.4 \sim 3.8 \ M_\odot$ donor star mass evolves and reproduces the present configuration of PSR J1614-2230. However the final NS high mass value is not easily reached. Indeed, to fit the current mass of the NS, it must have initially been at least of $1.6 \pm 0.1 \ M_\odot$. In the same way, the calculations made by Tauris, Langer & Kramida (2011) require a NS that was born with a mass greater than the canonical value of $1.4 \ M_\odot$ to fit the observed pulsar mass in PSR J1614-2230.

The standard model includes neither evaporation of the donor star by radio pulsar irradiation nor X-ray irradiation feedback. Evaporation leads the donor star to enhanced mass losses. This phenomenon was studied by Ruderman (1989) and Ruderman, et al. (1989). In these papers, the authors studied the effect of evaporation wind in the case of binary systems composed by a NS with very light companions ($< 0.1 \ M_\odot$) due to various types of radiation, during accretion phase or when this process has ended. One of the main objectives of their research was to find a possible explanation for the existence of isolated millisecond pulsars without a visible companion that has acted as its donor in a recycled scenario. The role of evaporation is essential to depict the evolution of certain binaries to the black widow state (see, e.g., Benvenuto, De Vito, & Horvath 2012).

On the other hand, irradiation feedback occurs during RLOF episodes, when matter falls onto the NS and releases X-ray irradiation that illuminates the donor star (Podsiadlowski 1991) first studied the effect of irradiation in LMXBs. For stars that have a thick enough convective zone, this phenomenon makes their structure to change considerably making its effective surface to become smaller. Accordingly, in some cases the donor star is unable to sustain the RLOF and becomes detached. Subsequent nuclear evolution may lead the donor star to experience RLOF again, undergoing a quasi-cyclic behaviour (Hameury, et al. 1993; Binning & Ritter 2004; Benvenuto, De Vito & Horvath 2014). This process may affect the evolution of the LMXBs, explaining the classical discrepancy between the millisecond pulsar and LMXB lifetimes (Pfahl, Rappaport & Podsiadlowski 2003).

Here, we shall show that it is possible to account for the masses, the orbital period, and the characteristics of the WD of PSR J0740+6620 system, provided that the system has a very low metallicity. Besides, we show that the NS in this system can reach its large mass without the necessity of being initially more massive than the canonical value. We shall also consider the capability of binary evolution models considering irradiation feedback to provide a plausible scenario for the formation of the PSR J0740+6620 system.

The remainder of this paper is organised as follows. In Section 2 we describe our stellar code. In Section 3 we expose the results we obtained and present a progenitor for PSR J0740+6620. Lastly, in Section 4 we review the main results presented in this paper and we give some concluding remarks.

2 OUR NUMERICAL MODEL

Our research was performed using the binary evolutionary code presented in Benvenuto & De Vito (2003). This code was updated by the inclusion of evaporation of the donor star and irradiation feedback. Every time the system is in a Roche Lobe Overflow (RLOF) state, the code works in a fully implicit way, solving the donor star’s structure together with the mass transfer rate, the increase/decrease of the mass of both stars in the system and the evolution of the orbital semi-axis. This method is numerically stable and allows for the calculation of mass transfer cycles (Benvenuto, De Vito, & Horvath 2012). When the system is detached, the code employs the standard Henyey technique. For further details, we refer the reader to Benvenuto, De Vito & Horvath (2014) and references therein. In our studies the normal star is the donor, i.e., the star that suffers RLOF, and the NS acts as an accreting compact object. In this work we shall take irradiation feedback into account but ignore evaporation since at these stages it is expected to be not relevant.

3 NUMERICAL RESULTS

In order to find a plausible progenitor for the PSR J0740+6620 system, we computed the evolution of binary systems initially composed by a NS and a normal star on the Zero Age Main Sequence. We considered donor stars with initial mass $M_2 = 1 \ M_\odot$, hydrogen mass abundance of $X = 0.7381$ and metallicities of $Z = 0.0174$ (the Solar value, see Asplund, et al. 2009, 0.0010, 0.0003 and 0.0001. The initial NS mass is assumed to be $1.4 M_\odot$ in all our simulations.

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1 As usual, the NS and donor star are indicated with subscripts 1 and 2 respectively.
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Figure 1. Final orbital period of the system as a function of the final mass of the donor star for different metallicities. The metallicity of the donor star is indicated for each curve. Black curves were calculated for this work and the red dot curve labeled as DVB12 corresponds to De Vito & Benvenuto (2012), whereas the other red curves were taken from Tauris & Savonije (1999). The horizontal thick line labeled as PSR J0740+6620 represents the observational data of this system.

Initially, in constructing these models we considered different values for the fraction $\beta$ of the matter transferred from the donor that is eventually accreted by the NS. The accretion onto the NS is limited by the so called Eddington accretion rate $\dot{M}_{\text{Edd}} = 2 \times 10^{-8} M_\odot \text{y}^{-1}$ (Podsiadlowski, Rappaport & Pfahl 2002). The choice of the parameter $\beta$ has a direct impact on the final NS mass, but has a minor effect on the evolution of the donor star. After some exploration of the parameters space we decided to assume conservative mass transfer, i.e. $\beta = 1$ in all our final calculations. Of course, lower values of $\beta$ and higher initial masses $M_2$ are possible and would eventually give other different solutions for the progenitor of PSR J0740+6620. Nevertheless, it is not the aim of this paper to provide a whole family of plausible solutions for the progenitor of PSR J0740+6620. It is well known that for systems that have donor stars with masses not too low, there is a rather well defined relation between the final donor mass and the orbital period, $M_2 - P_{\text{orb}}$ (see, e.g., Rappaport, et al. 1995). We employed these relations to find a system able to account for the observed masses and orbital period of PSR J0740+6620. Fig. 1 shows these relations for the metallicity values computed for this work. Each point on these curves represents the final state of the evolutionary track of one binary system. The characteristics observed for PSR J0740+6620 are reached by a system with $Z = 0.00010$. This is in qualitative concordance with the suggestion made by Cromartie, et al. (2019) based on the relations presented by Tauris & Savonije (1999). Following our calculations, we conclude that a system that undergoes conservative mass transfer and initially has $M_2 = 1 M_\odot$, $M_{\text{NS}} = 1.4 M_\odot$, $Z = 0.00010$ and $P_{\text{orb}} = 0.45 \text{ days}$ represents a plausible progenitor for PSR J0740+6620.

In addition, as stated above ($\S$ 2), we took into account the effects of irradiation feedback on the evolution of the system described above (with initial $M_2 = 1 M_\odot$, initial $P_{\text{orb}} = 0.45 \text{ days}$ and $Z = 0.00010$). We considered the case of $\alpha_{\text{irrad}} = 0.10$ which represents an intermediate case for the effects induced by irradiation on the evolution. Fig. 2 shows the evolution of the system considering irradiation and ignoring it. The irradiated system undergoes some mass transfer cycles. As it can be seen in Fig. 3 during the cyclic stage of mass transfer of irradiated models, the mass transfer rate from the donor star largely exceeds the Eddington Rate on very short timescales. Thus, even having assumed $\beta = 1$, some ma-
Figure 3. Donor mass transfer rate as a function of time for a system with initial mass $M_2 = 1\, M_\odot$ and initial orbital period $P_{\text{orb}} = 0.45$ days. The continuous red line corresponds to a system with irradiation feedback with $\alpha_{\text{irrad}} = 0.10$ and the black dashed curve corresponds to a system without irradiation. The horizontal line indicates the Eddington rate, below which material is lost from the system. This represents an obvious difficulty for getting high mass values for the accreting NS. A detailed calculation shows that even in this situation, the masses of the components $M_2$ and $M_1$ (NS mass) of the system are still compatible with the observations made by Cromartie, et al. (2019) (see Fig. 4). Hence, irradiation is not an unavoidable ingredient to successfully reach the observed parameters (masses and orbital period). So, for studying the present evolutionary state of PSR J0740+6620 this phenomenon may be neglected.

In what follows, we shall analyse three different conditions for the evolution of the donor star ignoring irradiation feedback. After the donor star detaches from its Roche Lobe, it has a thick hydrogen-rich envelope while the interior has a helium composition. Thus, initially we analysed the cases of donor models considering and ignoring diffusion. As we shall show below, these models do not cool down fast enough to account for the observations of a very cool helium-dominated atmosphere WD made by Beronya, et al. (2019). To reach such a state we had to remove all the remaining H in the donor star envelope. We did it when the donor attains its maximum luminosity on the other tracks assuming it has been converted into helium.

The evolutionary tracks for these three cases are presented in Fig. 5. The calculations without diffusion show a fast evolution to high effective temperature values and a subsequent slow and smooth cooling as a WD. Calculations were stopped at ages in excess of the Hubble time. Even so, the donor star remained far hotter than observed, making it to be incompatible with observations. It can be expected that models considering diffusion are more promising. Diffusion provides an hydrogen tail that reaches very hot layers inducing the occurrence of several thermonuclear flashes at the bottom of that rather outer layers (se, e.g., Benvenuto & De Vito 2004). Indeed, much hydrogen is burnt out making the star to cool down faster than the model without diffusion (see Fig. 6). However, as in the former case, models considering diffusion still remain hotter than observations for the age of the Universe. Notice that, apart from the temperature and luminosity, the outer stellar layers are still hydrogen rich.

The donor star model in which we have removed all H at its envelope initially reaches a very high temperature and luminosity because its outer layers became suddenly much more transparent. This should be considered as an unrealistic consequence of the procedure. This very high luminosity depends on the details of the artificial procedure performed to remove the remaining H. Fortunately, these details have no impact on the subsequent evolution of the object. The model quickly reaches a cooling track for an...
helium-rich WD finally reaches a temperature compatible with the observations made by Beronya, et al. (2019) in a time scale smaller than the age of the Universe. On the contrary, donor stars which still have H in their envelopes do not cool enough to become compatible with observations. Fig. 7 shows the evolution of the temperature in the three cases (H-rich envelope without and with diffusion, and He-rich envelope). After the age of 6.5 Gyrs, the curves begin to separate and the system which has a He dominated envelope cools down faster than the other models. Something similar happens with the luminosity (Fig. 8). For an He dominated envelope, luminosity suffers a pronounced decay, caused by the lack of H which acts as an insulator.

It can be considered that the so called “born-again” scenario proposed long time ago by Iben, et al (1983) is a promising process to make the star to loss all its hydrogen by a nuclear burning process. Although we found several hydrogen burning flashes, they were not strong enough to burn out all the remaining hydrogen. In any case, for PSR J0740+6620 some process should have happened to remove the remaining hydrogen, but the detailed physical process is still not clear at this moment.

4 DISCUSSION AND CONCLUSIONS

In this paper our motivation was to explore a possible origin for the very massive NS in PSR J0740+6620. Using the binary evolutionary code developed by our group, we searched for plausible progenitors for the binary system that contains this MSP. We considered a conservative system, i.e. all the matter lost by the donor, when it is below the $M_{\text{Edd}}$ rate, is accreted by the NS ($\beta = 1$), and examined different initial values for the mass of the donor star, the orbital period and metallicities. We analysed the effects of irradiation feedback on the evolution of the system, finding that both irradiated and non irradiated models provide plausible progenitors for PSR J0740+6620. However, binary evolution predicts a hydrogen rich envelope. Thus, we explored diffusion effects on the donor star and found that stars which have H-rich envelopes do not cool down fast enough to reach the very low effective temperature observed for its companion (Beronya, et al. 2019). If we remove the remaining hydrogen of the envelope of the donor star, we verified that the compact remnant of the donor star cools down fast enough to reach the observed effective temperature in a time scale smaller than the age of the Universe.

We found that the model with initial masses $M_1 = 1.4 M_\odot$ and $M_2 = 1 M_\odot$, orbital period $P_{\text{orb}} = 0.45$ days, and $Z = 0.00010$, accounts for the evolutionary status of the system observed by Cromartie, et al. (2019). Also, from an evolutionary point of view, we found that the envelope of the white dwarf should be hydrogen free, which is in nice agreement with the composition observed by Beronya, et al. (2019).

In our calculations we have found that the donor star experiences few thermonuclear flashes during which lead to a sudden increase of luminosity. These flashes do not burn all its remaining hydrogen leading to large the discrepancy with observations. Ev
identically, in our calculations some physical ingredient has a largely underrated relevance, or is simply lacking. One possibility is that the effects of diffusion have been underestimated and in reality they lead to stronger thermonuclear flashes. If so, much of the hydrogen would be burnt out but also some of it may be lost in a later flash driven RLOF. Another possibility is that evaporation of the donor is indeed non-negligible as we have assumed in calculations. All these possibilities warrant a future detailed exploration.

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