BAAA, Vol. 61B, 2020
A.M. Vásquez, P. Benaglia, F.A. Iglesias & M.A. Sgró, eds.

Asociación Argentina de Astronomía
Boletín de artículos científicos

Effect of tides on the orbital evolution of irradiated interacting binaries

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Resumen / Estudiamos la evolución de sistemas binarios interactuantes formados por una estrella de neutrones y una estrella ordinaria de tipo solar. Analizamos el efecto de mareas en la evolución de los elementos orbitales del sistema incorporándolo al código de evolución binaria desarrollado en nuestro grupo. Benvenuto, De Vito y Horvath estudiaron la evolución de estos sistemas considerando que la sincronización y circularización de la órbita ocurren instantáneamente. Además, consideraron los efectos de evaporación e irradiación, fenómenos que afectan profundamente la ocurrencia de los episodios de transferencia de masa. En sus estudios, encontraron un progenitor para el redback PSR J1723-2837 que permite una interpretación de tres datos observacionales (período orbital, temperatura y masa de la estrella donora), pero que no se ajusta a la derivada del período orbital observada. En este trabajo, consideramos el efecto de mareas entre episodios de transferencia de masa con el objetivo de estudiar el cambio del período orbital del sistema de manera detallada.

Abstract / We study the evolution of interacting binaries composed by a neutron star and an ordinary solar-like star. We analyse the effect of tides on the evolution of the orbital elements, incorporating them in the binary evolution code developed by our group. Benvenuto, De Vito and Horvath have studied the evolution of these systems considering that the synchronisation and circularization of the orbit occur instantaneously. Besides, they included irradiation feedback and evaporation, which are phenomena that deeply affect the occurrence of mass transfer episodes. In their studies, they found a progenitor for the PSR J1723-2837 redback that can explain the observed orbital period, temperature and mass of the donor star, but it fails to fit the observed orbital period derivative. In this work we consider the effect of tides between mass transfer episodes in order to study the change in the orbital period of the system in detail.

Keywords / stars: evolution — binaries: general — binaries: eclipsing

1. Introduction

Redbacks are eclipsing binary systems composed by a neutron star (NS) and a companion solar-like star between 0.2 and 0.4 $M_\odot$, with an orbital period between 0.1 and 1 day. In this work, we focus on the redback PSR J1723-2837, discovered by Faulkner et al. (2004). It has a rotational period of 1.86 ms and an almost circular orbit with $P = 14.76$ hr. The eclipses suggest that the pulsar companion is a non-degenerate extended star. Moreover, the spectral analysis made by Crawford et al. (2013), led this star to be classified between a G5 and a K0 spectral type main-sequence star, with an effective temperature of 5000–6000 K. These authors derived a companion mass range of $M_c = 0.4$–$0.7\ M_\odot$, and an orbital inclination angle between 30°–41°, assuming a pulsar mass in the range of $M_{NS} = 1.4$–$2.0\ M_\odot$. The derived radius of the companion star indicates that it is close to filling its Roche Lobe. Besides, they reported an orbital period derivative of -3.5×10^{-9} ss^{-1}, which is considerably too large to be allowed by the standard model of binary evolution.

Benvenuto et al. (2015b) studied the evolution of close binary systems considering evaporation and irradiation feedback, and assuming that after mass transfer the system instantaneously circularizes and synchornizes. Here, we relax the synchronization and circularization conditions and explore the effect of tides between mass transfer episodes. As tidal forces produce changes in the orbital period, it is expected that this effect directly affects the orbital period derivative.

In brief, tidal interaction occurs because of the presence of the NS, which introduces a force that elongates the donor star along the line between the centres of mass. If the rotational period of the star is shorter than the orbital period, then frictional forces on the surface of the star drag the bulge axis ahead of the line of centres. The resulting torque transfers angular momentum between the stellar spin and the orbit, while conserving the total angular momentum and diminishing the orbital and rotational energy. In consequence, the orbital parameters change, and stellar rotation tends to synchronise with the orbital motion, the orbit tends to circularise and the equatorial plane approaches the orbital plane.

2. Numerical Treatment

In our previous works (Benvenuto et al. 2015b, Benvenuto et al. 2015a, Benvenuto et al. 2014, Benvenuto et al. 2012) we have always considered the system to be in a circularised and synchronised state throughout the entire evolution. We now relax these approximations and study the effect of tidal interactions in between of two consecutive mass transfer episodes.

In order to get a general qualitative picture of tidal evolution, we study a simple model of equilibrium tide, which is described by assuming that the donor star is always in hydrostatic equilibrium (Hut 1981, Repetto & Nelemans 2014). Besides, we treat the NS as a point source.

As stated in Sec. 1., tidal interactions make the system lose orbital and rotational energy. Consequently, the system can asymptotically approach an equilibrium state or lead to an accelerated spiralling-in of the two stars (Alexander 1973; Hut 1980). Would the equilibrium state be reached, it would only be temporarily as it could be broken at any time due to a sink of angular momentum in the system caused by to magnetic braking (MB; Verbunt & Zwaan 1981; Rappaport et al. 1983) or gravitational waves (Hurley et al. 2002). We take into account both phenomena.

In order to add tides to our model, we integrated a full set of equations based on Hut's model for tidal evolution (Hut, 1980), and coupled them with the angular momentum loss by MB (Repetto & Nelemans, 2014) and gravitational wave radiation. To achieve this, we developed a code that calculates the evolution of the orbital elements that suffer changes due to tidal effects. These elements are the semi-major axis, the eccentricity, the inclination of the rotational angular momentum with respect to the orbital angular momentum, and the spin frequency of the star. To solve the set of equations, information about the binary system is required. In order to obtain it, we calculated an evolutionary track using the numerical code of Benvenuto & De Vito (2003) updated by the inclusion of evaporation of the donor star and irradiation feedback. We study a system composed by a normal, solar composition donor star of 1.25 $M_\odot$, evolving on a close binary system together with a 1.4 $M_\odot$ NS on a 0.75 day orbit, with a regime of irradiation feedback $\alpha_{\rm irrad} = 0.01$. These initial parameters were taken from Benvenuto et al. (2015b), in order to complete their investigation.

We also study linear (Zahn, 1966), quadratic (Goldreich & Nicholson, 1977) and quadratic with an extra factor of 50 (Belczynski et al., 2008) scaling for the viscosity due to turbulent convection with the tidal forcing frequency, $F_{\rm conv}$.

3. Results

We compute the evolution of the binary system that achieves the state observed for PSR J1723-2837 while calculating the structure of the donor star since it is in the Zero Age Main Sequence. Fig. 1 shows this star's evolution in a Hertzsprung-Russell diagram, and the effective temperature limits observed by Crawford et al.

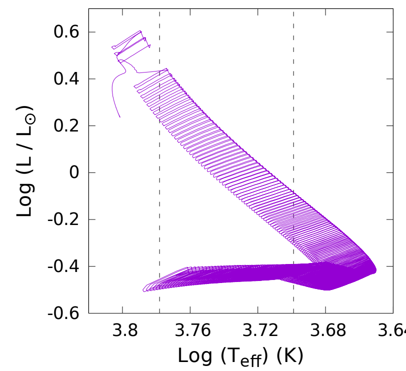


Figure 1: Hertzsprung-Russell diagram depicting the evolution of the donor star. Vertical dashed lines denote the lower and upper limit observed for the effective temperature (Crawford et al., 2013).

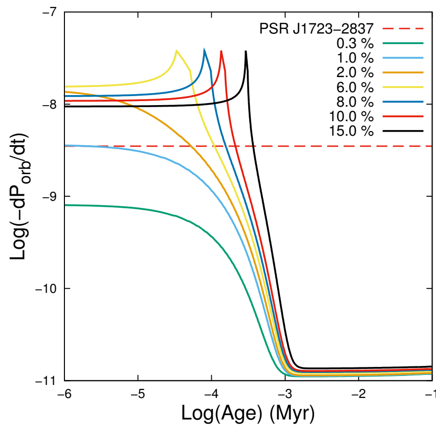
(2013) are marked by two vertical lines. The donor star undergoes a large number of Roche Lobe overflows (RLOFs) separated by detached stages, caused by irradiation feedback. We analyse the tidal effect on one of these pulses of mass transfer. As we focus on the evolution of the orbital period derivative, the analysis we make does not depend strongly on which pulse we use, since any other pulse would give similar results.

Observations of the binary system PSR J1723-2837 report an orbital period derivative of -3.5×10^{-9} ss^{-1}. Using three laws of the scaling for the viscosity due to turbulent convection with the tidal forcing frequency, $F_{\rm conv}$, we explore different values for the initial orbital and rotational period asynchronism in order to find in which systems the orbital period derivative better adjusts the observation. This exploration is presented in Fig. 2, where the first graphic corresponds to a linear $F_{\rm conv}$, the second to a quadratic $F_{\rm conv}$ and the third to a quadratic $F_{\rm conv}$ multiplied by 50. The orbital period derivative is reached by several systems where the rotational period of the companion is initially greater than the orbital period by a given percentage. Since tides affect the system during its entire evolution, one expects that the system has a small asynchronism. Hence, only the third law of $F_{\rm conv}$ (Belczynski et al., 2008) allows for systems with a smaller initial asynchronism to achieve the observed value of PSR J1723-2837 orbital period derivative.

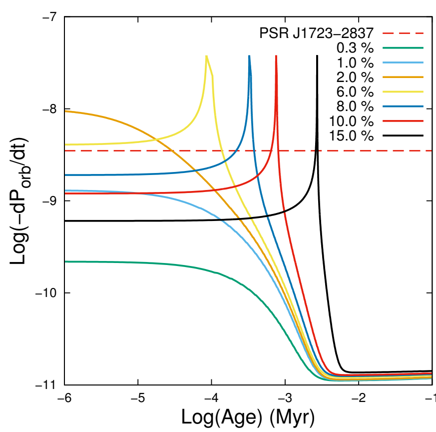
Fig. 3 shows how tides affect the orbital and rotational period in a time scale of a few centuries, after which both show the same behaviour, although they never synchronize. This is because MB constantly acts slowing down the rotation of the outer convective part of the star.

4. Conclusions

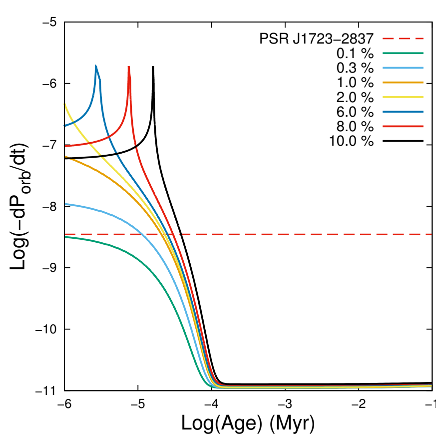
This study of the redback system PSR J1723-2837 is in continuity of Benvenuto et al. 2015b, which found a plausible progenitor that did not fit the observed orbital period derivative. Adding the physics of tides to our evolutionary code, we found three families of systems



(a) Linear



(b) Quadratic



(c) Quadratic *50

Figure 2: Orbital period derivative as a function of time for different laws for F_{conv}. Each curve corresponds to a system with initial rotational period greater (by a given percentage) than the initial orbital period. The orbital period derivative observed for PSR J1723-2837 is denoted with a dashed line.

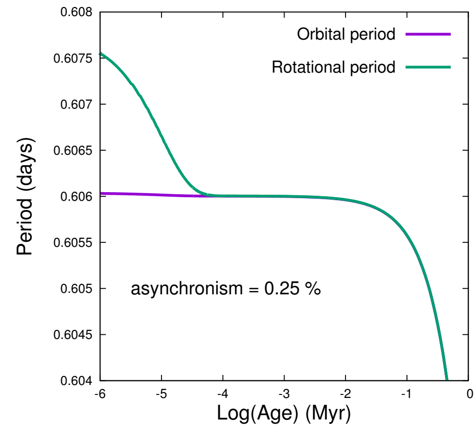


Figure 3: Orbital and rotational periods of the companion as a function of time, for a system with initial asynchronism of 0.25 % and F_{conv} quadratic multiplied by 50.

that reach this value. Each family corresponds to a different law of the scaling for the viscosity with the tidal forcing frequency. We analyse the initial orbital and rotational period asynchronism in each of these systems and conclude that the law proposed by Belczynski et al. (2008) is the most adequate, since it allows systems with small initial asynchronism to reach the orbital period derivative observed.

In a future work we plan to study the field of application of our binary evolutionary model together with the physics of tides. This may be interesting for different kinds of binary systems, either stellar or composed by other kind of objects.

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