Serb. Astron. J. № 202 (2021), 25 - 30
DOI: https://doi.org/10.2298/SAJ2102025P

UDC 52–423.4 : 524.387
Original scientific paper

INFLUENCE OF THE INITIAL ORBITAL PERIOD AND ACCRETION EFFICIENCY ON THE LOW-MASS BINARY EVOLUTION

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(Received: March 11, 2021; Accepted: April 26, 2021)

SUMMARY: This paper presents detailed evolutionary models of low-mass binary systems (1.25 + 1 $M_\odot$) with initial orbital periods of 10, 50 and 100 days and accretion efficiency of 10%, 20%, 50%, and a conservative assumption. All models are calculated with the MESA (Modules for Experiments in Stellar Astrophysics) evolutionary code. We show that such binary systems can evolve via a stable Case B mass transfer into long period helium white dwarf systems.

Key words. Stars: binaries: general – Stars: evolution – Stars: low-mass – Stars: white dwarfs

1. INTRODUCTION

The primary star in a binary system evolves faster than the secondary and through the envelope expansion may reach its Roche radius and start transferring mass onto the secondary star. Depending on the initial mass ratio, the mass gaining companion may expand fast, which results in a contact configuration or the system may evolve through stable mass transfer (Wellstein and Langer 1999).

In the case of initial mass ratios far from unity, the secondary star also fills its Roche lobe during the mass transfer and a so-called common envelope is formed (Nelson and Eggleton 2001). Also, when the primary has a largely convective envelope, it can expand rapidly and engulf the secondary (Ivanova et al. 2013). Due to friction of stars moving in an envelope, the angular momentum will decrease and the system will end up in a merger or as a system with a very short orbital period (De Kool 1990, Iben and Livio 1993, Taam and Sandquist 2000).

To avoid the dynamical Roche Lobe Overflow (RLOF) and subsequent common envelope evolution, the initial system mass ratio has to be less than some critical value of about 1.2-1.5 (Soberman et al. 1997). In this stable mass transfer scenario, one of the major uncertainties in evolutionary calculations is the efficiency of the mass transfer: what fraction (β) of the transferred mass is actually accreted by the secondary star? The conservative evolution assumes that the mass and angular momentum of the binary system are conserved and non-conservative evolution assumes that a fraction of the mass and angular momentum leaves the binary system. Concerning massive binaries, Petrovic et al. (2005) showed that an accretion efficiency of about 10% agrees with the observed Wolf-Rayet + O binary systems the best.

Various studies on different classes of wide low mass binaries have shown that the mass transfer must often be very nonconservative. Such objects include, for example, long period binaries with a helium white dwarf (Landsman et al. 1993, Vennes et al. 1998, Merle et al. 2014) and long period binaries hosting a helium core burning, B-type subdwarf (sdB) star (Østensen and van Winckel 2011, Vos et al. 2012, 2013, Deca et al. 2012, Barlow et al. 2012, 2013). The formation of a helium white dwarf or sdB stars requires that the primary star loses most of its envelope

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during the red giant phase. Han et al. (2002, 2003, 1995) and Chen et al. (2013) considered that such systems evolve through stable mass transfer, since the common envelope evolution would, in general, result in orbital periods far shorter than what is observed.

In this paper, detailed evolutionary models of the low-mass 1.25 + 1 $M_\odot$ binaries are presented in an attempt to reproduce the long-period helium white dwarf binary systems. The paper is organized as follows: Section 2 provides details about the calculated evolutionary models. Section 3 presents details about the orbital evolution of the modelled binaries. The summary is given in Section 4.

2. EVOLUTIONARY MODELS

For calculation of evolution of the low-mass binary models presented in this paper, the MESA (Modules for Experiments in Stellar Astrophysics) code was used (Paxton et al. 2011, 2013, 2015, 2018).

Thermonuclear reactions are calculated according to Caughlan and Fowler (1988) and Angulo et al. (1999). The MESA opacity tables are made by combining the radiative opacities from Ferguson et al. (2005) and OPAL opacities by Iglesias and Rogers (1993, 1996) with the electron conduction opacities from Cassisi et al. (2007).

The MESA code calculates simultaneously the evolution of both stars within a binary system. The mass transfer happens via the L_1 Lagrangian point and its rate is calculated according to the Ritter scheme (Ritter 1988). The composition of the accreted material is identical with the donor's current surface composition. For the case of an inefficient mass transfer, the angular momentum loss follows Soberman et al. (1997) where the fixed fractions of the transferred mass are lost from the gainer isotropically.

To evaluate the influence of the initial orbital period and accretion efficiency on the evolution of the long-period WD binary systems, models with the same initial masses (1.25 + 1 $M_\odot$), but for various initial orbital periods (100, 50 and 10 days) and accretion efficiencies of 100%, 50%, 20% and 10% are calculated. All modelled binary systems evolve via the Case B mass transfer. This means that the primary star in all considered binaries has completed its core hydrogen burning phase before filling its Roche lobe. The metallicity of all models is set to be 0.02. Stellar wind mass loss and stellar rotation are not taken into account. Table 1. lists all binary models presented in this paper.

In all modelled binary systems, the primary star exhausts all hydrogen in its core before the Case B mass transfer to the secondary star begins. The mass transfer stops due to shrinking of the primary star and its transition into a helium white dwarf.

In binary systems with the initial orbital periods of 100 and 50 days and a conservative assumption, the helium white dwarfs of 0.40 $M_\odot$ and 0.37 $M_\odot$ are formed. The secondary star, in both cases, is still a main sequence star, but with an increased mass (1.86 $M_\odot$ and 1.88 $M_\odot$) and increased central hydrogen abundance due to the rejuvenation process (0.54 and 0.53). During the Case B mass transfer phase, the orbital period in those systems increases to 503 and 300 days respectively.

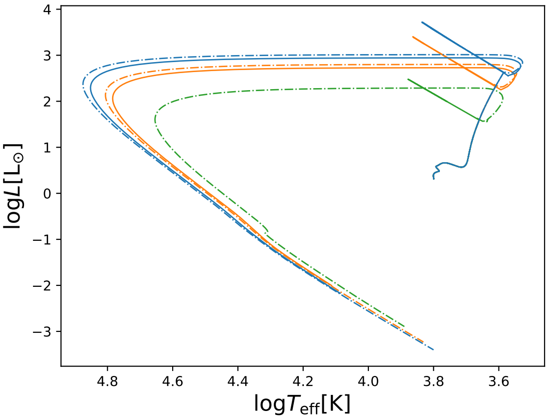

Fig. 1: Evolutionary tracks of the primary star in a binary system 1.25 + 1 $M_\odot$ with an initial orbital period of 100 days (blue), 50 days (orange) and 10 days (green), with the assumption of conservative evolution (solid lines) and accretion efficiency of 10% (dash dotted line).

In both systems, when the secondary star finishes its main sequence evolution, it becomes a red giant but its radius does not reach the Roche radius before helium is ignited in its core. After all helium is exhausted and a CO core is formed, the envelope of the secondary expands and mass transfer to the primary (helium white dwarf) starts.

The 1.25 + 1 $M_\odot$ system with an initial orbital period of 10 days evolves into a contact phase during the Case B mass transfer due to an extremely high mass transfer rate. At this time, the primary is a 1.20 $M_\odot$ red giant with 0.23 $M_\odot$ helium core and the secondary is a 1.05 $M_\odot$ main sequence star.

Fig. 1 shows evolutionary tracks of the primary star in a binary system of 1.25 + 1 $M_\odot$ with initial orbital period of 100 days (blue), 50 days (orange) and 10 days (green), with the assumption of conservative evolution (solid lines) and accretion efficiency of 10% (dash dotted lines). It is shown, as expected, that the primary star in the system with the largest initial orbital period expands the most before the mass transfer can start (blue solid line). Its luminosity is the highest and its effective temperature the lowest during the mass transfer. Decreasing the initial orbital period to 50 days does not significantly change the evolution of the primary (orange solid line) and its evolutionary track is just slightly shifted. However, for the initial period of 10 days, the evolution is significantly different, as the system enters the contact quickly after the onset of the Case B mass transfer (green solid line).

Also shown in Fig. 1 is that, for systems that evolve through the stable Case B mass transfer, the accretion efficiency does not significantly influence

Table 1: Case B low-mass binary models presented in this paper; p$_{in}$ - initial orbital period in days; m_2/m_1 - initial mass ratio; β - accretion efficiency; $m_{1,f}$ - final primary mass; $m_{2,f}$ - final secondary mass, both in $M_\odot$; ev.phase1 - final modelled evolutionary phase of the primary; ev.phase2 - final modelled evolutionary phase of the secondary; p_f - final orbital period, $m_{1,f}/m_{2,f}$ - final mass ratio.

p_{in}	m_2/m_1	β	$m_{1,f}$	ev.phase1	$m_{2,f}$	ev.phase2	p_f	$m_{1,f}/m_{2,f}$
100	0.80	1	0.40	He WD	1.86	RG CO core	503.3	0.21
100	0.80	0.5	0.40	He WD	1.42	RG CO core	558.3	0.28
100	0.80	0.2	0.40	He WD	1.17	RG CO core	588.0	0.34
100	0.80	0.1	0.40	He WD	1.08	RG He core	596.1	0.37
50	0.80	1	0.37	He WD	1.88	RG CO core	300.1	0.19
50	0.80	0.5	0.37	He WD	1.44	RG He core	334.2	0.26
50	0.80	0.2	0.37	He WD	1.18	RG He core	359.1	0.31
50	0.80	0.1	0.37	He WD	1.09	RG He core	357.5	0.34
10	0.80	1	1.20	RG He core	1.05	MS	9.6	1.14
10	0.80	0.5	1.14	RG He core	1.05	MS	9.8	1.09
10	0.80	0.2	0.32	He WD	1.18	RG He core	104.5	0.27
10	0.80	0.1	0.32	He WD	1.09	RG He core	104.2	0.29

the evolutionary path of the primary star (blue and orange dash-dotted lines). Only for the system that enters contact with the conservative assumption, the accretion efficiency of 10% allows it to avoid the contact and evolve through the stable Case B mass transfer into a helium white dwarf - red giant system (green dash-dotted line). This is expected as the secondary in this case accretes a significantly smaller amount of matter lost by the primary and does not expand enough to fill its Roche lobe during the Case B mass transfer.

The evolution of the secondary star in the conservative case does not change significantly by decreasing the initial orbital period from 100 to 50 days. However, with the shortest initial period (p_{in}=10 days), the secondary expands significantly and due to this, the binary system enters the contact phase. If an accretion efficiency of 10% is assumed, the luminosity and effective temperature of the secondaries are not radically altered during the mass transfer by mixing processes.

Fig. 2 shows the evolution of the internal structure for the primary and the secondary star in the 1.25 + 1 $M_\odot$ binary system with an initial orbital period of 100 days and accretion efficiency of 10%. The top black line shows the total mass of the star. Blue regions are indicating the nuclear burning zones and green diagonally hatched areas show the convective regions. The blue dotted line represents the mass of the helium core.

The left panel shows the internal evolution of the primary star. It can be seen that the core hydrogen burning phase lasts until about 4000 Myrs and then the envelope hydrogen burning starts as the star expands into a red giant. At about 5000 Myrs, the Case B mass transfer starts. During this mass transfer, the primary loses most of its hydrogen envelope and becomes a 0.4 $M_\odot$ helium white dwarf. The right panel shows the internal evolution of the secondary star. During the Case B mass transfer, it becomes a rejuvenated main sequence star, the size of its hydrogen burning core increases by almost 0.2 $M_\odot$ and its mass reaches 1.08 $M_\odot$. Convective envelopes are visible for both stars as they enter the red giant phase and subsequent mass transfer.

3. ORBITAL EVOLUTION

All calculated binary systems with initial orbital periods of 100 and 50 days evolve through a stable Case B mass transfer. The systems with an initial orbital period of 10 days avoid contact only for lower values of accretion efficiency (10% and 20%).

The Fig. 3 shows the orbital period evolution as a function of mass ratio for all modelled 1.25 + 1 $M_\odot$ binary systems. While the mass ratio decreases the most for conservative evolution (solid lines), the orbital period increases the most in systems with the largest mass loss, i.e. for the accretion efficiency of 10% (dash-dotted lines).

For the initial orbital period of 100 days, the masses of the formed white dwarfs are 0.40 $M_\odot$ for all assumed accretion efficiencies, and for the initial orbital period of 50 days, the resulting white dwarfs have masses of 0.37 $M_\odot$. In the case of an initial orbital period of 10 days, the conservative evolution and accretion efficiency of 50% lead to a contact during the Case B mass transfer as the secondary significantly expands and fills its Roche lobe. The stable Case B mass transfer happens if the assumed accretion is 20% or 10% and the resulting mass of the white dwarf is 0.32 $M_\odot$ in both cases.

The resulting mass of the secondary star obviously depends on the accretion efficiency. For an initial orbital period of 100 days, the resulting red giant masses are 1.86, 1.42, 1.17 and 1.08 $M_\odot$ for accretion efficiencies of 100%, 50%, 20% and 10% respectively. For 50 days, the resulting red giant masses are 1.88, 1.44, 1.18 and 1.09 $M_\odot$. For 10 days, the systems that avoid contact end up with secondaries of 1.18 and 1.09 $M_\odot$ (Table 1).

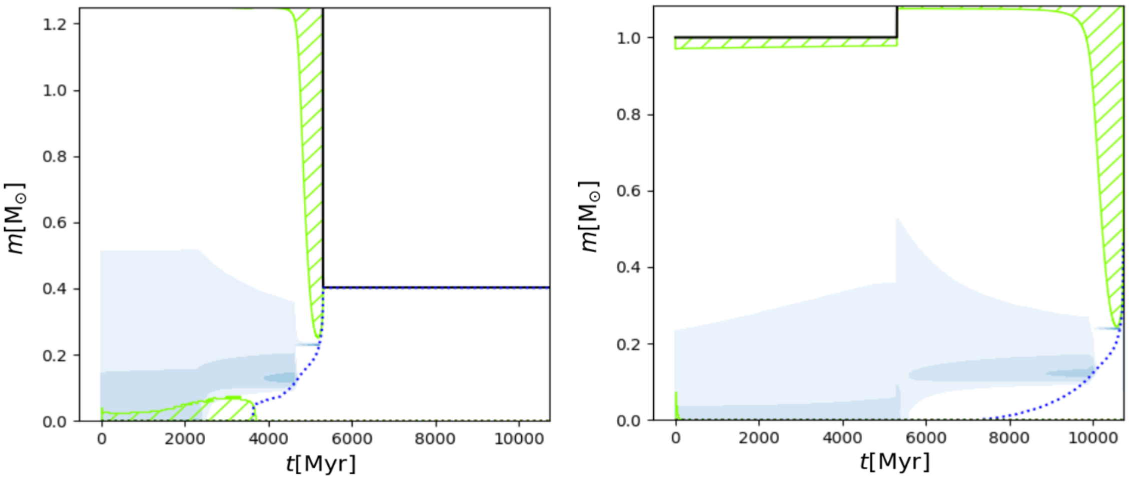

Fig. 2: Kippenhahn plots of the primary (left) and the secondary (right) star in binary systems 1.25 + 1 $M_\odot$ for initial orbital period of 100 days and accretion efficiency of 10%. X-axis shows time in Myrs and y-axis shows stellar mass in Solar masses. Top black line presents the total stellar mass. Blue regions mark nuclear burning zones, darker shades indicate large intensity. Green diagonally hatched areas indicate convection regions. The blue dotted line presents the mass of the helium core.

The final orbital period in the white dwarf + main sequence/red giant phase depends both on the initial orbital period and accretion efficiency. It increases with increase of the initial orbital period and with decrease of accretion efficiency, as the orbit widens due to the mass loss from the system. For example, in the case of an initial orbital period of 100 days, the resulting orbital periods are 503, 558, 588 and 596 days for conservative evolution and 50%, 20% and 10% accretion efficiency, respectively.

Fig. 4 shows the mass transfer rate as a function of the secondary star mass in all calculated binary systems: 1.25 + 1 $M_\odot$ with an initial period of 100 days (blue lines), 50 days (orange lines) and 10 days (green lines), with the assumption of conservative evolution during the mass transfer (solid lines) and accretion efficiency of 50% (dashed lines), 20% (dotted lines) and 10% (dash-dotted lines).

Maximum values of the mass transfer rate for conservative models with an initial orbital period of 100 and 50 days are extremely high, in the order of magnitude of $10^{-1} M_\odot$/yr (solid blue and orange line). The maximum values of the mass transfer rate for binary systems where the accretion efficiency of 50% is assumed are slightly lower, in the order of magnitude of $10^{-2} M_\odot$/yr (dashed blue and orange line). For the accretion efficiency of 10%, the maximum mass transfer rate is $10^{-3} M_\odot$/yr (dotted blue, orange and green line). Despite those high mass transfer rate values, the secondary star in presented models does not expand enough to fill its Roche lobe. The maximum mass transfer rate decreases with the drop in accretion efficiency because of the larger angular momentum loss from binary systems that results in a longer orbital period.

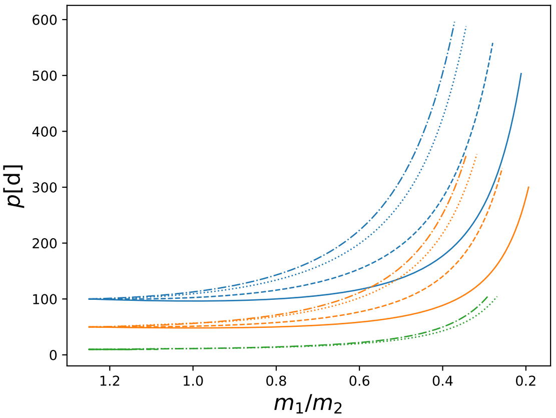

Fig. 3: The orbital period vs. mass ratio m_1/m_2 in binary system 1.25 + 1 $M_\odot$ with an initial orbital period of 100 days (blue lines), 50 days (orange lines) and 10 days (green lines), with the assumption of conservative evolution during the mass transfer (solid lines) and accretion efficiency of 50% (dashed lines), 20% (dotted lines) and 10% (dash-dotted line).

The binary systems with the shortest initial orbital period (10 days) and a conservative or a 50% accretion efficiency assumption evolve into the contact phase. It can be seen in Fig. 4 that, in those two systems, the mass transfer rate increases rapidly after the onset of the Case B mass transfer (green solid and dashed lines) and reaches values above 1 $M_\odot$/yr. Due to this, the secondary star in those systems expands enough to fill its Roche lobe. The evolution of contact systems most likely proceeds via a common envelope phase. Due to friction of stars moving in an envelope, a significant amount of angular momentum is lost from such systems and they end up in a merger or with a very short orbital period.

Fig. 4 also shows that for each accretion efficiency, the secondary mass increases more for a shorter initial orbital period. This is because the maximum of the mass transfer rate increases with the decrease of the initial orbital separation between the binary components. This is clearly visible for conservative binary systems with initial orbital periods of 100 and 50 days (solid blue and orange line).

The modelled binary systems with the initial orbital period of 100 days evolve into 500 to 600 days period, low-mass binaries and reproduce well the observed wide white dwarf - main sequence binary systems, such as HR 1608 and IP Eri (Landsman et al. 1993, Merle et al. 2014). The observed systems have orbital periods of 903 and 1071 days, respectively and masses of the white dwarfs are estimated to be 0.40 and 0.43 $M_{\odot}$. While our calculations produce somewhat shorter orbital periods, the obtained WD masses (0.40 $M_{\odot}$) fit the observations very well. While the secondary mass and the mass ratio are not known for IP Eri, the calculated main sequence secondary masses (1.08 - 1.86 $M_{\odot}$) are in good agreement with the observed main sequence mass in HR 1608 of 1.35 $M_{\odot}$. The observed mass ratio 0.296 of HR 1608 also falls within the modelled mass ratio range of 0.21 to 0.37. However, it should be pointed out that the systems coming out of the mass transfer are expected to be circularized while the observed ones have eccentricity of about 0.25 - 0.30, which the presented models can not explain.

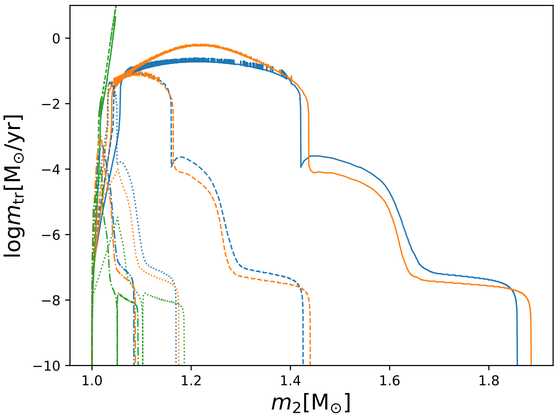

Fig. 4: The mass transfer rate as a function of the secondary mass in a binary system 1.25 + 1 $M_{\odot}$ with initial period of 100 days (blue lines), 50 days (orange lines), and 10 days (green lines), with assumption of conservative evolution during the mass transfer (solid lines) and accretion efficiency of 50% (dashed lines), 20% (dotted lines), and 10% (dash-dotted lines).

4. SUMMARY

The MESA code was used to calculate detailed evolutionary models of low-mass binaries with different orbital periods, assuming conservative and non-conservative mass transfer with different accretion efficiencies. The systems that evolve via a stable Case B mass transfer evolve into long-period binaries consisting of a white dwarf and a main sequence/red giant star. These models indicate a possible channel to produce long-period binaries via stable mass transfer.

To investigate progenitor evolution of long period low-mass binaries and evaluate the influence of the initial orbital period and accretion efficiency on evolution of the considered low mass binary systems, models with the same initial masses 1.25 + 1 $M_{\odot}$, but various initial orbital periods (100, 50 and 10 days) and accretion efficiencies (conservative, 50%, 20% and 10%) are calculated.

Out of 12 calculated models, 10 evolve via a stable Case B mass transfer phase and become low-mass wide binary systems. After the mass transfer, the primary star that has lost most of its envelope becomes a helium white dwarf. The secondary star in all systems is still a core hydrogen burning main sequence star that evolves further into a red giant. The orbital periods of the calculated models are in the range of 100 to 600 days.

As expected, a lower accretion efficiency increases the chance of a binary system evolving via a stable Case B mass transfer. Also, due to the higher mass loss from binary systems in case of lower accretion efficiencies, the resulting orbit is wider, i.e. the orbital period is larger.

The maximum mass transfer rate decreases with drop in accretion efficiency, because of a larger angular momentum loss from binary systems that results in a longer orbital period. The secondary mass increases more for a shorter initial orbital period, because the maximum of the mass transfer rate increases with the decrease of the initial orbital separation between the binary components.

The modelled binary systems with the initial orbital period of 100 days evolve into 500 to 600 days period low-mass binaries and can present a possible channel of evolution producing long period white dwarf - main sequence/ red giant binary systems.

Acknowledgements – During the work on this paper the authors were financially supported by the Ministry of Education and Science of the Republic of Serbia through the contract 451-03-9/2021-14/200002.

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УТИЦАЈ ПОЧЕТНОГ ОРБИТАЛНОГ ПЕРИОДА И ЕФИКАСНОСТИ АКРЕЦИЈЕ НА ЕВОЛУЦИЈУ МАЊЕ МАСИВНИХ ДВОЈНИХ СИСТЕМА

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УДК 52–423.4 : 524.387
Оригинални научни рад

Овај рад представља детаљне еволуционе моделе двојних звезда са масама 1.25 $M_\odot$ и 1 $M_\odot$ са различитим почетним орбиталним периодима (10, 50 и 100 дана). Такође, осим конзервативне еволуције која претпоставља одржање масе у двојном систему, еволуција система са ефикасношћу акреције од 10%, 20%, 50% је такође моделирана. Сви модели су израчунати са MESA (Modules for Experiments in Stellar Astrophysics) нумеричким еволуционим кодом. Резултати показују да овакви системи могу да еволуирају кроз стабилан Case B трансфер масе у двојни систем са дугачким орбиталним периодом који садрже бели патуљак и звезду главног низа.