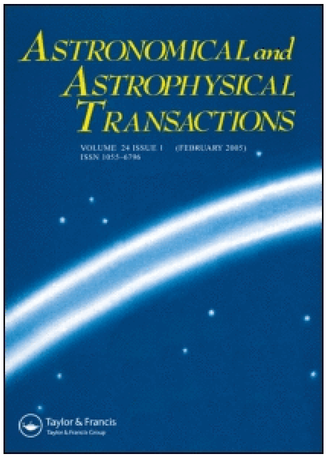

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On the evolutionary model of progenitors of extreme horizontal branch objects after critical Roche lobe overfilling

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It has been shown quite recently that dwarf B stars, which are extreme horizontal branch (EHB) objects, in high probability all belong to binary systems. We study in detail the mass and angular momentum loss from the giant progenitors of subdwarf B stars in an attempt to clarify why binarity must be a crucial factor in producing EHB objects. It was found that considerable shrinkage of the orbit can be achieved after Roche lobe overfilling by the EHB progenitor, because of the combined effect of angular momentum loss from the red giant and appreciable accretion on its low-mass companion on the hydrodynamic timescale of the donor, which results in the formation of a helium white dwarf with mass roughly equal to half the solar mass, thus evading the common envelope stage. A simple approximating analytical formula for mass loss rate from the Roche-lobe-filling giant donor is proposed and the ranges of its applicability are studied.

Keywords: Binaries; Close stars; Evolutionary model

1. Introduction

Underluminous subdwarf B (sdB) stars are thought to be helium-burning stars with very-low-mass hydrogen envelopes. Effective temperatures (above 25 000 K) and surface gravities ($\log g > 5$) place them on extreme horizontal branches (EHBs), i.e. they appear in the same region of the $T_{\rm eff}$–$\log g$ plane as evolutionary tracks for core helium-burning stars with core masses of about $0.5M_\odot$ and extremely thin (not more than $0.02M_\odot$) inert hydrogen envelopes. It is currently accepted that EHBs form as a result of enhanced mass loss on the red giant branch (RGB) when the degenerate helium core loses almost all the hydrogen convective envelope close to the RGB tip but the core goes on to ignite helium despite the dramatic mass loss and may appear as an sdB star. Quite recently it has been discovered that most EHBs are components of binary systems with orbital periods $P_{\rm orb} \approx 0.12$–27 days in a pair with

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a main-sequence low-mass companion [1]. It remains unclear why binarity seems to play a crucial role in the formation of sdB stars.

2. Analysis of mass loss, mass transfer and angular momentum loss

To clarify the nature of the EHB progenitors, we have calculated the evolution of the orbit of a binary assuming that the progenitor of the sdB star filled in its critical Roche lobe when the former was approaching the tip of RGB during its nuclear evolution. We used the computer code sse.f [2] to follow the evolution of the primary until the donor approached its critical Roche lobe. Once the donor fills in its Roche lobe, subsequent evolution depends on the relation between the primary radius R_1 and the Roche lobe radius R_L. If, for instance, the donor reacts to mass loss and mass transfer by further expanding its envelope while the radius of the critical Roche lobe decreases, a considerable shrinkage of the orbit can be expected even on the dynamic timescale $\delta t \approx 10^4$ years. We computed the period change caused by mass loss from the system, mass interchange and additional angular moment loss by matter corotated at the Alfvén radius $R_\mathrm{A} = kR_1$, k being a model parameter [3]. The mass loss rate by the donor is defined by the Roche lobe overfilling $\Delta R = R_1 - R_\mathrm{L}$ as $M_1 = (M_1/t_\mathrm{HD})(\Delta R/R_\mathrm{L})^3$, $t_\mathrm{HD} \approx R_1/V_\mathrm{s}$ being the hydrodynamic timescale. To avoid the t_HD calculation which requires knowledge of the temperature-dependent sound velocity V_s, we introduce the free-fall timescale $t_\mathrm{ff} \approx R_1/V_\mathrm{esc}$ and, using the fact that the escape velocity $V_\mathrm{esc} \gg V_\mathrm{s}$, we set $t_\mathrm{HD} \approx 100(R_1^3/GM_1)^{1/2}$, avoiding unphysically high mass loss rates; in our case, typically $t_\mathrm{HD} \approx 10^5$–$10^6$ s, which is roughly one order of magnitude shorter than donor's thermal timescale. The Roche lobe radius R_L is found from the empirical fit given in [4]. The mass accretion rate is set by a predefined value of the mass transfer effectiveness parameter $Q = \dot{M}_2/\dot{M}$. The increment in the stellar radius is found from the mass–radius–age relation for a single star as

$$\Delta(\log R_1) = \log\left(\frac{M_1}{M_1^\circ}\right) - t_\mathrm{KH}\frac{\mathrm{d}(\log M_1)}{\mathrm{d}t}, \tag{1}$$

where $t_\mathrm{KH} = GM_1^2/R_1L_1^\circ$ is the Kelvin–Helmholtz timescale, and M_1° and L_1° are the primary mass and luminosity, respectively, at the moment of Roche lobe overfilling. The upper limit of the Roche lobe overfilling rate was adopted close to the effective size H of the neck near the first Lagrangian point and in computations mostly was kept around $H/R_\mathrm{L} \approx 1\%$ (for more details see [5]).

3. Discussion

It was found that the final orbit of the system is quite sensitive to the initial separation of the components, the ratio of mass transfer rates, the mass loss rate and the corotation radius. For larger initial separations the system has time only for moderate orbit shrinkage, when the primary star contracts again and its radius 'falls' again below the Roche lobe. Roche lobe contraction follows the contraction of the orbit, but the donor, having lost a certain amount of its mass, contracts more quickly than the Roche lobe; so its radius again becomes smaller than R_L, and the mass transfer is disrupted. However, if the stars are initially close enough to each other, the timescale of the donor's contraction is longer than the timescale of the Roche lobe contraction; so the donor overfills its Roche lobe until the orbit shrinks dramatically. Smaller values of the corotation radius do not enable effective orbit shrinkage to occur. With high accretion rates ($\dot{M}_2 \geq 0.3\dot{M}$) the system loses angular momentum much more effectively, and this favours close binary formation. The timescale for the formation of a close binary following Roche lobe filling is several millions of years, which is comparable with the thermal timescale of the low-mass companion. We have found that a simple approximating formula for the mass loss rate

$$\dot{M} = C\frac{L}{MR^{3.2}} \qquad (2)$$

($C \approx -1.5 \times 10^{-3}$, L, M and R being the luminosity, mass and radius, respectively, of the star in solar units) holds for the phase of Roche lobe filling irrespective of the value of the parameter k, the mass accretion rate Q over more than one order of magnitude changes in the radius R_1 of the donor and the separation d of the components. The value of the numerical constant C depends on the choice of the hydrodynamic timescale t_{HD} but the relation for $\dot{M}$ holds for different values of t_{HD} (see figure 1 where the linear dependence is also depicted; note that considerable departures from the linear relation occur when the radius of donor becomes

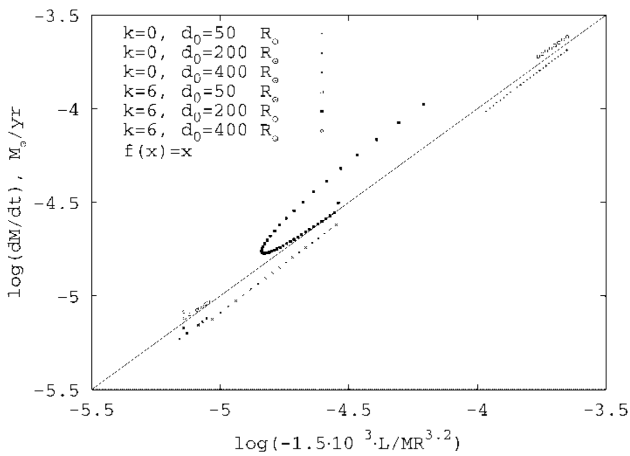

Figure 1. $\dot{M}$ as a function of $-1.5 \times 10^{-3}L/MR^{3.2}$ for different values of k and d_0. The straight line $f(x) = x$ is superimposed to demonstrate the precision of the empirical formula. $M_{1\,\mathrm{init}} = 0.95M_\odot$, $M_{2\,\mathrm{init}} = 0.23M_\odot$, $Q = 0.3$, the constant at t_{HD} is 112 and the Roche lobe overfilling limit is 2%.

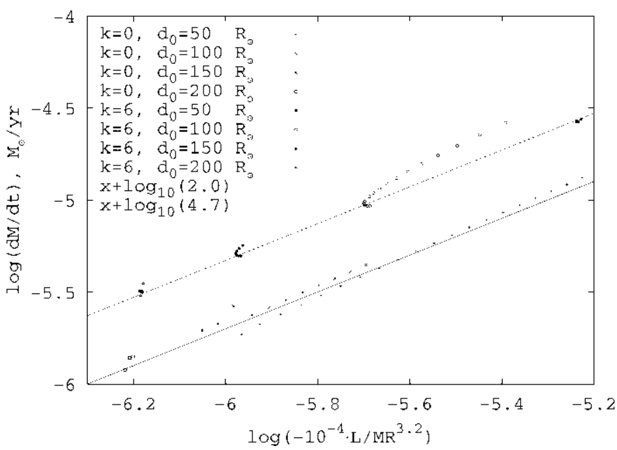

Figure 2. $\dot{M}$ as a function of $-10^{-4}L/MR^{3.2}$ for different values of k and d_0. $M_{2\,\mathrm{init}} = 0.35M_\odot$ and the other parameters are the same as in figure 1.

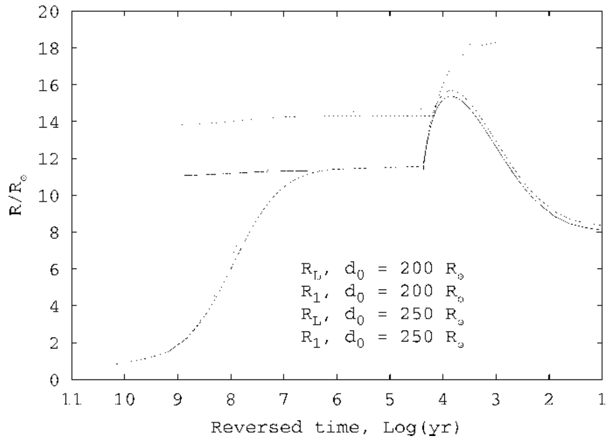

Figure 3. The evolution of the Roche lobe radius R_{L} and the donor's radius R_1 for different initial semimajor axis values d_0. $k = 6$ and the other parameters are the same as in figure 1. The time on the x axis is counted backwards.

appreciably smaller than the Roche lobe size; C is also different for the regime when the trend of the stellar radius changes to the opposite with the star remaining within its Roche lobe). Equation (2) holds for donor masses up to about $0.3M_{\odot}$. With higher donor masses, C becomes dependent on the value of the parameter k; the value of the power of R also tends to change slightly from trend to trend. This is illustrated in figure 2, which is analogous to figure 1 but with $M_2 = 0.35$. It follows from the figure that the trends for $k = 0$ and $k = 6$ do not lie on the same straight line; the coefficients C are -2.0×10^{-4} and -4.7×10^{-4}, respectively.

Figure 3 represents the evolution of the Roche lobe and the donor's radius at two different initial separations d_0. After reaching its Roche lobe, the donor radius follows R_{L}. It is seen that for larger initial separations the system has time for only moderate orbit shrinkage, when the primary star contracts again and its radius 'falls' again below the Roche lobe.

4. Conclusions

Our approach enabled us to determine the ranges of initial parameters of a binary for which effective mass transfer and angular momentum loss result in the formation of a close binary with properties characteristic for EHBs. The initial separation, the angular momentum loss parameter and the mass transfer rate parameter play the most important roles. We conclude that binarity indeed favours EHB formation. Assuming that the EHB progenitors belong to the binaries with initial separations of $(100–150)R_{\odot}$ and fill in their Roche lobe while being close to the RGB tip, we have found that considerable shrinkage of the orbit can be achieved because of the combined effect of angular momentum loss and appreciable accretion on its low-mass companion on the hydrodynamic timescale of the donor, resulting in the formation of a helium white dwarf with a mass of about $0.5M_{\odot}$. Sufficiently high accretion rates and large Alfvén radius values are the prerequisite conditions for the formation of the binaries with EHBs according to the proposed scenario.

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