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On the Evolutionary History of Progenitors of EHBs and Related Binary Systems from their Observed Properties

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Abstract. It has been shown quite recently (Morales-Rueda *et al.* 2003) that dB stars, 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 sdB stars in an attempt to clarify why binarity must be a crucial factor in producing EHB objects. Assuming that the progenitors of EHB objects belong to binaries with initial separations of a roughly a hundred solar radii and fill in their critical Roche lobes while close to the tip of red giant branch, we have found that considerable shrinkage of the orbit can be achieved due to a combined effect of angular momentum loss from the red giant and appreciable accretion on its low mass companion on the hydrodynamical timescale of the donor, resulting in formation of helium WD with masses roughly equal to a half solar mass and thus evading the common envelope stage. A simple approximative analytical formula for mass loss rate from Roche lobe filling giant donor has been proposed depending on mass, luminosity and radius of donor.

1. Introduction

Underluminous sdB stars are thought to be helium-burning stars with very low-mass hydrogen envelopes. Effective temperatures ($> 25\,000\,K$) and surface gravities ($\log g > 5$) place them on the EHB, i.e., they appear in the same region of $T_{\rm eff} - \log g$ plane as evolutionary tracks for core He burning stars with core masses of about $0.5\,M_\odot$ and extremely thin ($\leqslant 0.02\,M_\odot$) inert hydrogen envelopes. It is currently accepted that EHBs form due to enhanced mass loss on the RGB when the degenerate helium core loses almost all of its hydrogen convective envelope close to the RGB tip but the core goes on to ignite helium despite dramatic mass loss and may appear as an sdB star. Quite recently it has been discovered that most of EHBs are components of binary systems with orbital periods $P_{\rm orb} \sim 0\overset{\rm d}{.}12 - 27^{\rm d}$ in pairs with MS low-mass companions. It remains unclear why binarity seems to play a crucial role in 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 a progenitor of sdB star filled in its critical Roche lobe when the former during its nuclear evolution was approaching the tip of the RGB. We used the Hurley *et al.* (2000) computer code *sse.f* to follow 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

Roche lobe radius $R_{\rm L}$. 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 dynamical timescale $\delta t \sim 10^4$ yrs. We computed period change caused by mass loss from the system, mass interchange and additional angular moment loss $K = \dot{J}/J$ by matter corotated at the Alfven radius $R_{\rm A}$:

$$K = \frac{2}{3}\, k^2 \left(\frac{R_A}{d}\right)^2 \frac{M}{M_1\, M_2}\, \dot{M}\ , \qquad (2.1)$$

where $k = R_{\rm A}/R_1$, d is the semi-major axis of orbit (Tout & Hall 1991). Mass loss rate by the donor is defined by the Roche lobe overfilling $\Delta R = R_1 - R_{\rm L}$ as

$$\dot{M}_1 = \frac{M_1}{t_{\rm HD}}\left(\frac{\Delta R}{R_{\rm L}}\right)^3\ , \qquad (2.2)$$

$t_{\rm HD} \sim R_1/V_{\rm s}$ being hydrodynamical timescale. To avoid $t_{\rm HD}$ calculation that requires knowledge of temperature–dependent sound velocity $V_{\rm s}$, we introduce a free-fall timescale $t_{\rm ff} \sim R_1/V_{\rm esc}$ and, using the fact that escape velocity $V_{\rm esc} \gg V_{\rm s}$, we set $t_{\rm HD} \simeq 100 \cdot \sqrt{R_1^3/GM_1}$ avoiding unphysically high mass loss rates; in our case typically $t_{\rm HD} \sim 10^5 - 10^6$ sec, which is roughly one order of magnitude shorter than the donor's thermal timescale. The Roche lobe R_L radius is found from the empirical fit of Eggleton (1983). The mass accretion rate is set by a predefined value of the mass transfer effectiveness parameter $Q = \dot{M}_2/\dot{M}$. The increment of the sellar radius is found from the mass-radius-age relation for a single star as

$$\Delta \log R_1 = \log \frac{M_1}{M_1^o} - t_{\rm KH} \frac{d \log M_1}{dt}\ , \qquad (2.3)$$

$t_{\rm KH} = GM_1^2/R_1 L_1^o$ being the Kelvin–Helmholtz timescale; M_1^o and L_1^o are the primary mass and luminosity 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 $H/R_{\rm L} \approx 1\%$ (for more details see Pustynski & Pustylnik 2006).

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 rate to 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 "drops" again below the Roche lobe. Roche lobe contraction follows the contraction of the orbit, but the donor, having lost certain amount of its mass, contracts quicker than the Roche lobe, so its radius becomes again smaller than $R_{\rm L}$, and the mass transfer disrupts. 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. With high accretion rates ($\dot{M}_2 \geqslant 0.3\,\dot{M}$) the system loses the angular momentum much more effectively, and this favors close binary formation. The timescale for formation of a close binary following the Roche lobe filling is several millions of years, which is comparable to the thermal timescale of the low mass companion. We have found that a simple approximating formula for the mass loss rate

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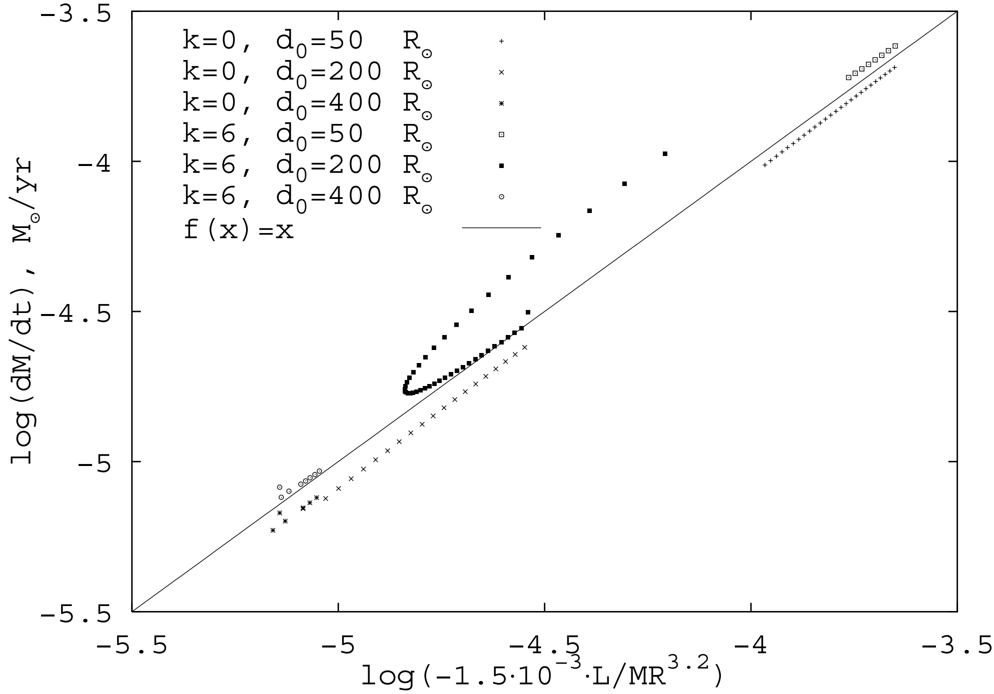

Figure 1. $\dot{M}$ as a function of $-1.5 \cdot 10^{-3}\, L/MR^{3.2}$ for different values of k and d_0. A straight line $f(x) = x$ is superimposed to demonstrate the precision of the empirical formula. $M_{1\,\mathrm{init}} = 0.95\, M_{\odot}$, $M_{2\,\mathrm{init}} = 0.23\, M_{\odot}$, $Q = 0.3$,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

$\dot{M} = -1.5 \times 10^{-3}\, L/MR^{3.2}$ holds for the phase of Roche lobe filling irrespective of the value of parameter k, mass accretion rate Q over more than one order of magnitude changes in the radius of the donor R_1 and separation of the components d. The value of numerical constant depends on the choice of the hydrodynamical time scale t_{HD} but the relation for $\dot{M}$ holds for different values of t_{HD} (see Figure 1 where linear dependence is also depicted, notice that considerable departures from linear relation occur when the radius of donor becomes appreciably smaller than the Roche lobe size; numerical constant is also different for the regime when the trend of stellar radius changes for the opposite with star remaining within its Roche lobe).

Figure 2 demonstrates semi-major axis evolution for different initial separations. The biggest value of $d_0 = 1500\, R_{\odot}$ corresponds to the case when the donor does not reach its Roche lobe during the time of nuclear evolution. With $d_0 = 1200\, R_{\odot}$, the overfilling occurs at the top of the donors evolution as red giant, so the separation only experiences slight growth due to mass loss. Only with small initial separations effective orbital shrinkage may occur.

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 formation of a close binary with properties characteristic for EHBs. The most important role plays initial separation, the angular momentum loss parameter and the mass transfer rate parameter.

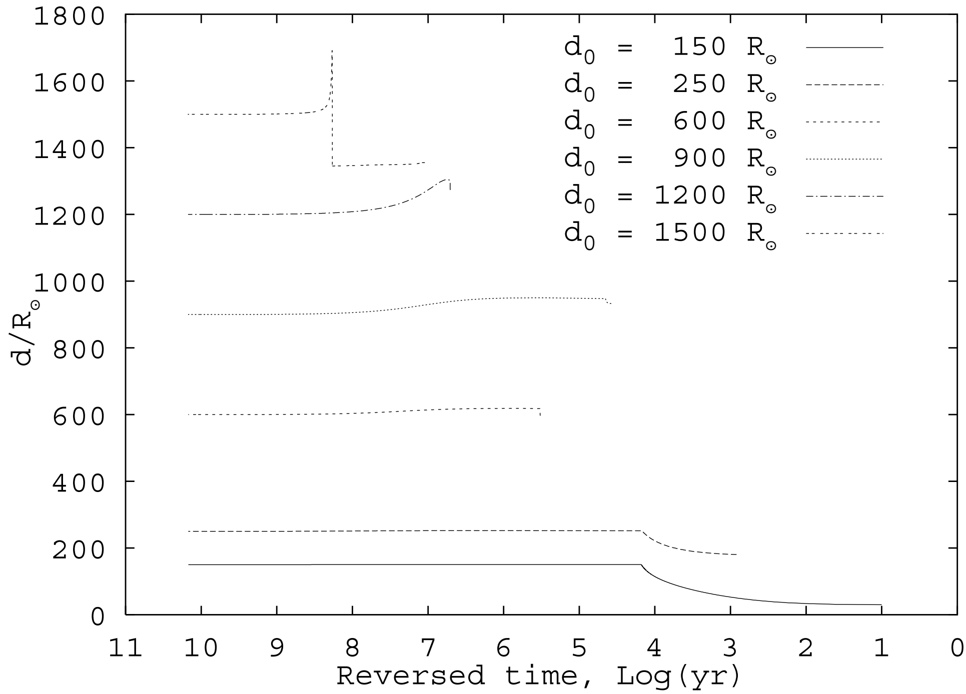

Figure 2. Separation d evolution for different initial semi-major axis values.

We conclude that binarity indeed favors 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 due to the combined effect of angular momentum loss and appreciable accretion on its low mass companion on the hydrodynamical timescale of the donor, resulting in formation of HeWD with masses about $0.5\, M_{\odot}$. Sufficiently high accretion rates and large Alfven radius values are the prerequisite conditions for the formation of the binaries with EHBs according to the proposed scenario.

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