ON THE EVOLUTIONARY HISTORY OF PROGENITORS OF EHBS AND RELATED BINARY SYSTEMS BASED ON ANALYSIS OF THEIR OBSERVED PROPERTIES

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ABSTRACT. It has been shown quite recently (Morales-Rueda *et al.*, 2003) that dB stars, extreme horisontal branch (EHB) objects in high probability all belong to binary systems. Assuming that the progenitors of EHB objects belong to the binaries with initial separations of a roughly a hundred solar radii and fill in their critical Roche lobes when being close to the tip of red giant branch, we have found in our earlier study 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. Far UV upturn phenomenon discovered in elliptical galaxies and spiral galaxy bulges was interpreted in terms of predominant contribution from EHB objects (Dorman, O'Connell, Rood, 1995). This circumstance can provide a reasonable constraint on the initial masses of EHB progenitors and thus the ages of EHB objects.

Key words: Stars: binaries: close.

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 EHB, i.e. they appear in the same region of $T_{\rm eff} - \log g$ plane as evolutionary tracks for core He burning with core masses of about $0.5\,M_\odot$ and extremely thin ($\leq 0.02\,M_\odot$) 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 hydrogen convective envelope close to the RGB tip but the core goes on to ignite helium despite dramatic mass loss and may appear as sdB star. Quite recently it has been discovered that most of EHBs are components of binary systems with orbital periods $P_{\rm orb} \sim 0^{\rm d}.12 \div 27^{\rm d}$ in pair with MS low mass companion. In our earlier study of evolution of the orbit resulting in formation of EHBs when the donor star being close to the tip of RGB fills in its critical Roche lobe and enhanced mass loss and angular momentum loss ensues we restricted our analysis for initial donor masses slightly less than one solar mass (Pustynski & Pustylnik, 2007). Here we extend our treatment assuming that initial mass of progenitor can be somewhat higher, up to $M_1 = 1.25\,M_\odot$. According to (Dorman, O'Connell, Rood, 1995) the ages of globular clusters and elliptical galaxies where EHBs are observed range between 6 and 11 Gyrs. We have found similarly to our earlier findings that with an enhanced mass loss rate (roughly by a factor of 2) compared to a standard rate predicted by Reimers formula during the RGB evolutionary stage. Evolution of the He burning core proceeds smoothly being virtually independent of the properties of an inert low mass hydrogen convective envelope. Below we briefly describe our method of analysis and discuss the implications for the evolutionary history of EHBs.

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

To clarify the nature of the EHB progenitors, we have calculated evolution of 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 RGB. We used (Hurley, Pols, Tout, 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_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_A:

$$K = \frac{2}{3}\,k^2 \left(\frac{R_A}{d}\right)^2 \frac{M}{M_1\,M_2}\,\dot{M}\ , \qquad (1)$$

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

$$\dot{M}_1 = \frac{M_1}{t_{HD}}\left(\frac{\Delta R}{R_L}\right)^3\ , \qquad (2)$$

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

$$\Delta \log R_1 = \log \frac{M_1}{M_1^o} - t_{KH}\frac{d \log M_1}{dt}\ , \qquad (3)$$

$t_{KH} = GM_1^2/R_1L_1^o$ being Kelvin-Helmholtz timescale, M_1^o and L_1^o are the primary mass and luminosity at the moment of Roche lobe overfilling. Due to exponential dependence of ΔR on the mass loss rate, joint application of the Eqs. (2) and (3) may result sometimes in unphysically rapid growth of the donor's radius. Actually, the extent of overfilling is limited by the slit width between the stellar surface and the Roche lobe. We may estimate the effective size of the neck near the first Lagrangian point. The neck cross-section is represented as

$$S \simeq 2\pi\frac{\gamma RT}{\mu}\frac{R_L^3}{GM_1}\ , \qquad (4)$$

$\gamma = C_p/C_v$, μ molar mass. So linear measure of the neck is $l/R_L \simeq 3V_\mathrm{s}/V_\mathrm{esc}$. Considering this diameter as chord to the Roche lobe, one may estimate the relative height scale by simple geometry as $H/R_L \simeq 1 - \sqrt{1 - l^2/4R_L^2}$. Calculus gives $H/R_L \approx 1\%$. So, we should restrict the admissible Roche lobe overfilling rates by several percent.

3. Discussion

It was found in our earlier study (Pustynski & Pustylnik, 2007) 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_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 ($\dot{M}_2 \geq 0.3\,\dot{M}$) 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. For stars with initial mass $M_{1\,\mathrm{init}} = 1.25\,M_\odot$ and enhanced mass loss by the margin given above during RGB evolutionary stage we confirm the validity of the basic conclusions concerning the final outcome of evolution of orbit. However for $M_{1\,\mathrm{init}} = 1.25\,M_\odot$ EHB object will be formed in roughly 4.8 Gyrs.

The Fig. 1 represents evolution of Roche lobe and the donor's radius at two different initial separation d_0. After reaching its Roche lobe, the donor radius follows R_L. It is seen that for larger initial separations the system have time only for moderate orbit shrinkage, when the primary star contracts again and its radius "falls" again below the Roche lobe. The initial masses of the components in Figures 1, 3, 4 are $M_{1\,\mathrm{init}} = 0.95\,M_\odot$, $M_{2\,\mathrm{init}} = 0.23\,M_\odot$ and in Fig. 2 $M_{1\,\mathrm{init}} = 1.25\,M_\odot$, $M_{2\,\mathrm{init}} = 0.23\,M_\odot$.

The Fig. 2 illustrates influence of the angular momentum loss parameter k on evolution the system. It follows from the figure that effective angular momentum loss is necessary for close binary formation: smaller value of k do not allow the orbit to contract significantly during the stage of mass interchange.

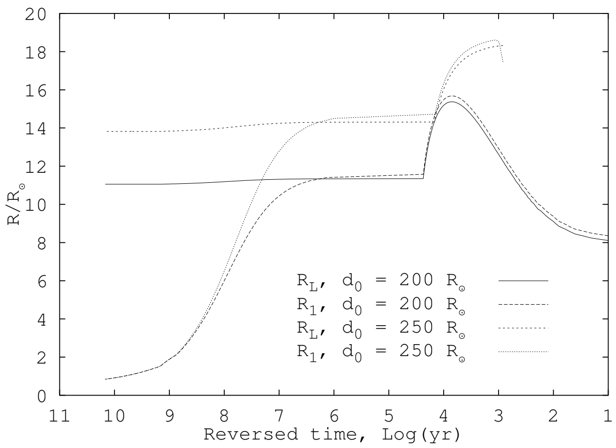

Figure 1: R_L and R_1 evolution for different initial semi-major axis values d_0. $Q = 0.3,\ k = 6$. The time on the x-axis is counted backwards, so that the zero point is the final point of the model computation.

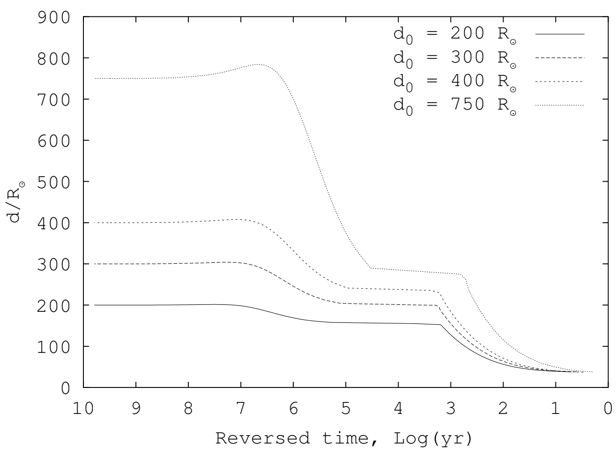

Figure 2: Separation evolution for different initial values of semi-major axis of orbit and mass of the donor $M_1 = 1.25M_\odot$.

The Fig. 3 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 donor's 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.

The Fig. 4 represents thermal mass radius exponent $\zeta_{\rm th} = (\partial R_2/\partial M_2)_{\rm th}$, adiabatic mass radius exponent $\zeta_{\rm ad} = (\partial R_2/\partial M_2)_{\rm ad}$ and Roche lobe mass radius exponent $\zeta_{\rm R_L} = (\partial R_L/\partial M_2)_*$ computed for different momentum loss parameters k and mass transfer effectiveness parameters Q. We followed (Ritter, 1999) to adopt a constant value for thermal mass exponent, so on the Fig. 4 $\zeta_{\rm th} \equiv -0.3$. The expression for $\zeta_{\rm R_L}$

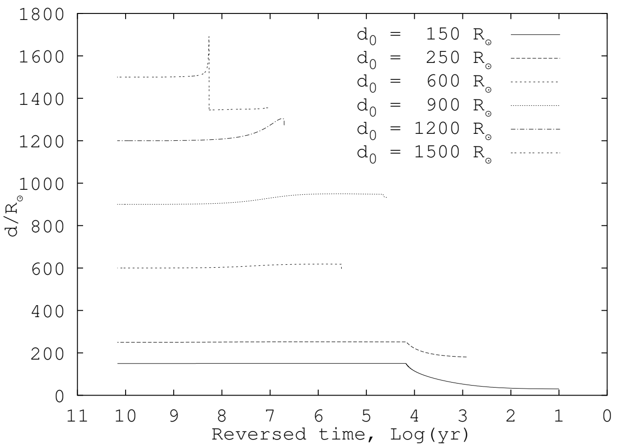

Figure 3: Separation d evolution for different initial semi-major axis values.

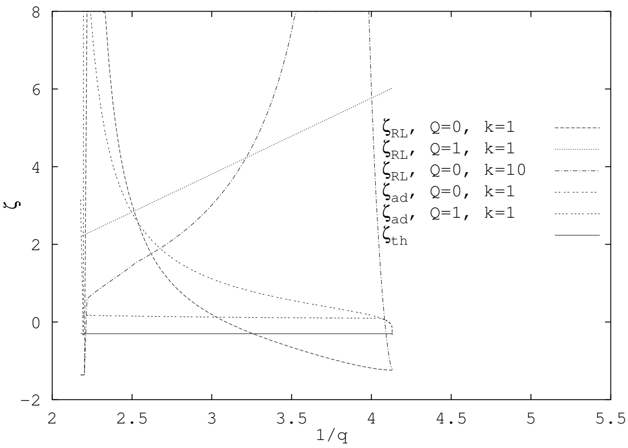

Figure 4: Thermal mass radius exponent $\zeta_{\rm th}$, adiabatic exponent $\zeta_{\rm ad}$ and Roche lobe mass radius exponent $\zeta_{\rm R_L}$ as functions of mass ratio, for different k and Q.

was also taken from (Ritter, 1999), $\zeta_{\rm ad}$ was calculated following (Soberman, Phinney, van den Heuvel, 1997).

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. 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 $0.5\,M_{\odot}$.

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