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The Initial–Final Mass Relation for Close Low–Intermediate-Mass Binaries (Non-conservative Case)

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Abstract. Employing Eggleton's stellar evolution code, we carry out 150 runs of non-conservative Population I binary evolution calculations with the initial primary mass between 1 and 8 $M_\odot$, the initial mass ratio $q = M_1/M_2$ between 1.1 and 4 and the onset of Roche lobe overflow (RLOF) at the early, middle or late Hertzsprung gap. We assume that 50 per cent of the mass lost from the primary during the RLOF is accreted on to the secondary, the other 50 per cent is lost from the system, carrying away the same specific angular momentum as the centre of mass of the primary. We find that the remnant mass depends on when the RLOF begins in the Hertzsprung-gap and the dependency increases with the primary mass. The remnant mass, however, does not depend much on the initial mass ratio, as compared to conservative cases. For $q_\mathrm{i} = 1.1$, we fit a formula for the remnant mass as a function of the initial mass $M_{1\mathrm{i}}$ of the primary and the radius of the primary at the onset of RLOF with an error less than 2.61 per cent.

1. Computation

The parameter space for the model grid is three dimensional – primary's initial mass $M_{1\mathrm{i}}$, initial mass ratio $q_\mathrm{i} = M_1/M_2$, and primary's radius R_1 at the onset of RLOF. The initial orbital period is a function of $M_{1\mathrm{i}}$, q_i and R_1. Our primary initial masses range from 1.0 to 8.0 $M_\odot$ at roughly equal intervals in $\log M_{1\mathrm{i}}$ ($M_{1\mathrm{i}} = 1.0$, 1.26, 1.6, 2.0, 2.5, 3.0, 4.0, 5.0, 6.3 and 8.0 $M_\odot$), the initial mass ratio from 1.1 to 4.0 (q_i =1.1, 1.5, 2.0, 3.0, 4.0) and $\log R_1$ has 3 values, $\log R_\mathrm{MS} + 0.1(\log R_\mathrm{HG} - \log R_\mathrm{MS})$, $0.5(\log R_\mathrm{HG} + \log R_\mathrm{MS})$ and $\log R_\mathrm{HG} - 0.1(\log R_\mathrm{HG} - \log R_\mathrm{MS})$, where R_MS and R_HG are the maximum radius on the main sequence and in Hertzsprung gap respectively for a given initial mass. The three values correspond to onset of RLOF at early HG, middle HG or late HG (see Fig. 1).

RLOF is included via the following boundary condition:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = C \max\Big[0, (\frac{r_\mathrm{star}}{r_\mathrm{lobe}} - 1)^3\Big], \tag{13}$$

where $\mathrm{d}M/\mathrm{d}t$ is the rate of change of mass of the star, r_star is the radius of the star, r_lobe is the radius of its Roche lobe and C is a constant. Here we take $C = 500\,M_\odot\,\mathrm{yr}^{-1}$.

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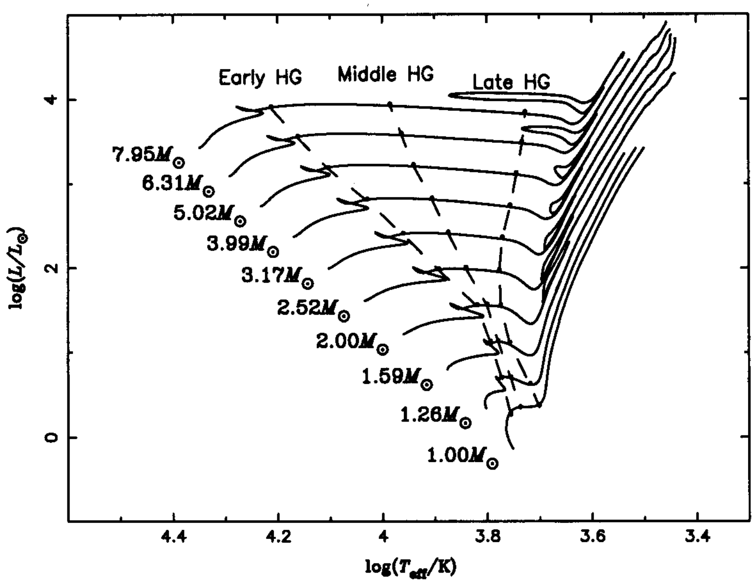

Figure 1. The evolution tracks of single stars with masses between 1 and 8 $M_\odot$. The three dashed lines, from left to right, indicate the position of an early HG, middle HG and late HG defined in this paper.

During RLOF, the change of the angular momentum of the system ΔJ is:

$$\frac{\Delta J}{J} = \frac{(1-\beta)\Delta M_1 M_2}{M_1(M_1+M_2)}, \tag{14}$$

where J is the angular momentum of the system. We take $\beta = 0.5$ in our calculations.

2. Results

We give the evolutionary tracks of the primary of a binary system. As seen in Fig. 2, there are two episodes of mass transfer. However in the second episode, the mass loss rate is much higher than in Han, Tout, & Eggleton (2000, hereinafter paper I). The code breaks down on the helium main sequence owing to hydrogen shell flashes. We compare some models which have formed CO cores and find that our models have larger CO cores than those in paper I with the same initial masses and mass ratios. This is caused by the convective overshooting in our models. The overshooting makes the nuclear reaction region larger, and the central temperature rises, and helium burning begins earlier. A similar effect appears in C-burning.

Another result from our calculations is that the mass difference between primary remnants with different initial mass ratios becomes much smaller than that in paper I (see Fig. 3). We also calculate non-conservative evolution without

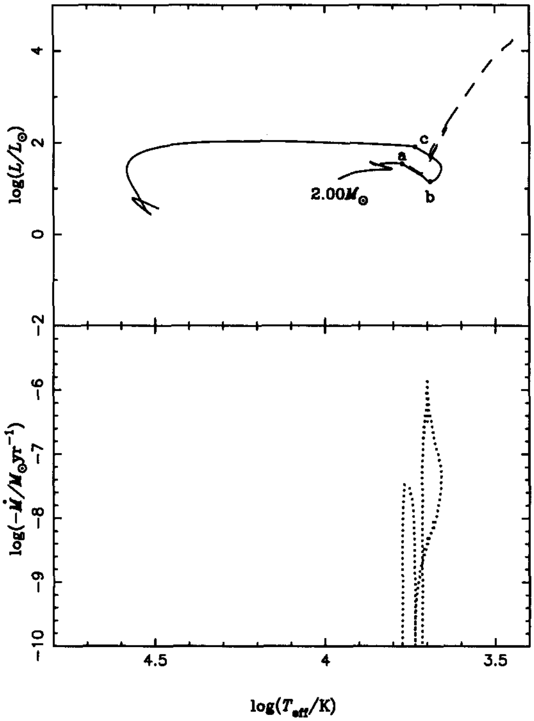

Figure 2. Evolutionary track (solid line of the top panel) of the primary of a Pop I binary system with initial parameters of $M_{1\mathrm{i}} = 2\,M_\odot$, $q_\mathrm{i} = M_1/M_2 = 1.5$ and $P_\mathrm{i} = 3.139$ days (late HG). The points a, b, and c indicate the beginning of RLOF, the minimum luminosity during RLOF and the end of the last episode of RLOF respectively. The evolutionary track of a $2\,M_\odot$ Pop I single star is shown as a dashed line for the purpose of comparison. The mass-transfer rate is plotted as dotted line in the bottom panel.

convective overshooting. The result is illustrated in Fig. 4. The two figures tell us that the weak dependence of remnant mass on initial mass ratio results from our non-conservative evolution assumption. Such a result may be related to the mass-transfer rate during RLOF.

Fig. 5 shows the effects of overshooting on remnant masses for $q_\mathrm{i} = 1.1$. There is almost no effect for low-mass binaries ($M_{1\mathrm{i}} \leq 1.6\,M_\odot$), and the effect increases with the initial primary mass.

Remnant masses hardly depend on the initial mass ratios. Therefore we fit the remnant mass $M_{1\mathrm{f}}$ as a function of the initial primary mass $M_{1\mathrm{i}}$ and the radius R_1 of the primary at the onset of RLOF with an error less than 2.61 per cent for $q_\mathrm{i} = 1.1$:

$$m_{1\mathrm{f}} = \frac{A_1 - A_2 m_{1\mathrm{i}} + A_3 m_{1\mathrm{i}}^2}{10000 - A_4 m_{1\mathrm{i}} + A_5 m_{1\mathrm{i}}^2}, \qquad (15)$$

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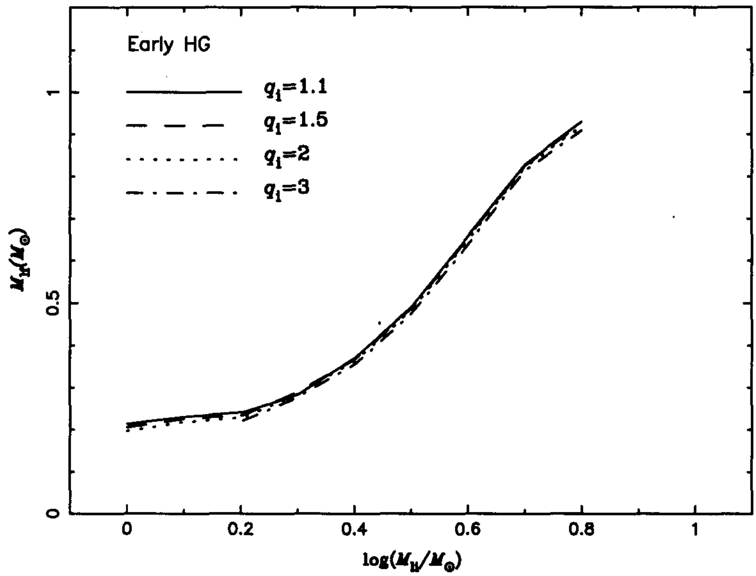

Figure 3. Remnant white dwarf(WD) masses after RLOF which begins at early HG.

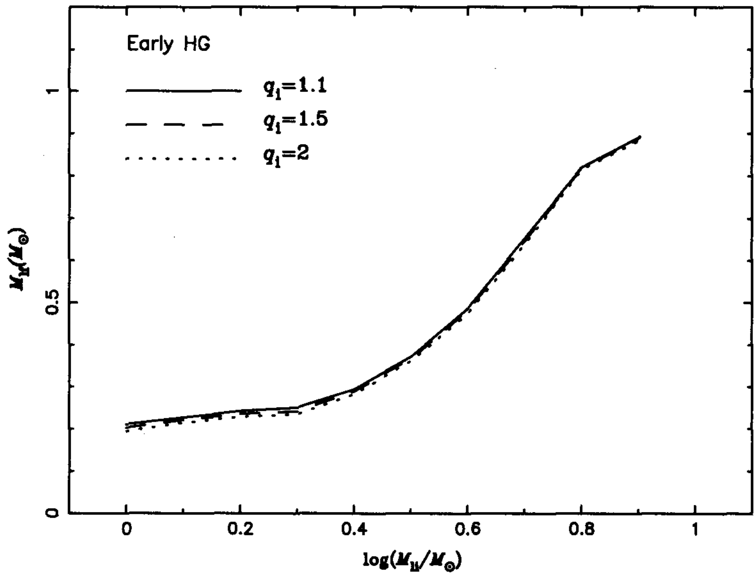

Figure 4. Similar to Fig. 3, but without overshooting.

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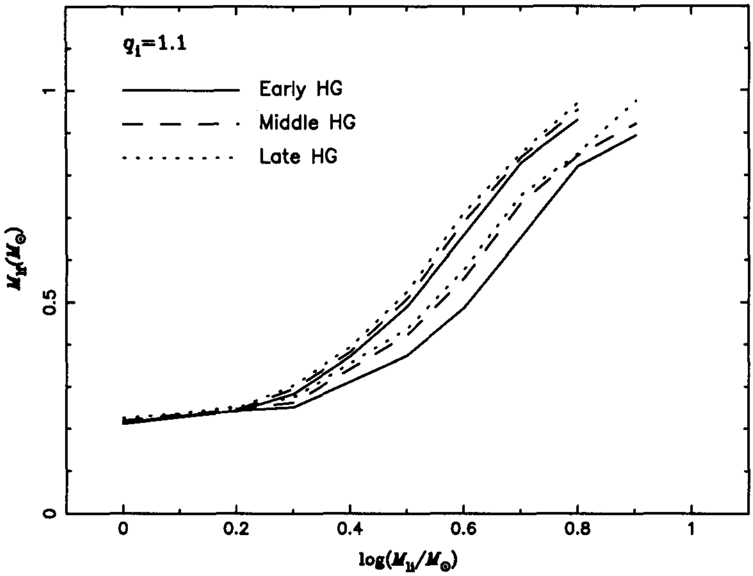

Figure 5. The remnant masses for initial $q_\mathrm{i} = 1.1$. The upper three lines are with convective overshooting while the lower three are without convective overshooting.

where $m_\mathrm{1f} = M_\mathrm{1f}/M_\odot$, $m_\mathrm{1i} = M_\mathrm{1i}/M_\odot$, and

$$A_i = B_{i,1} + B_{i,2}D + B_{i,3}D^2. \tag{16}$$

The coefficients $B_{i,j}$ $(i = 1,5;\ j = 1,3)$ are given in Table 1, and D is defined by

$$D = \frac{2\log(R_1/R_\odot) - 3D_1 + D_2}{D_2 - D_1}, \tag{17}$$

where

$$D_1 = \frac{0.13985 + 1.398(\log m_\mathrm{1i}) + 18.645(\log m_\mathrm{1i})^{2.5}}{1 - 1.3317(\log m_\mathrm{1i}) + 19.197(\log m_\mathrm{1i})^2} \tag{18}$$

and

$$D_2 = \frac{0.29903 + 1.4096(\log m_\mathrm{1i}) + 9.6322(\log m_\mathrm{1i})^2}{1 + 2.6066(\log m_\mathrm{1i}) + 0.5432(\log m_\mathrm{1i})^2}. \tag{19}$$

Here D_1 and D_2 are $\log(R_1/R_\odot)$ at early and late HG in Fig. 1, respectively. As the remnant mass does not depend much on q_i, the equation can be used for $1.1 \le q_\mathrm{i} \le 3$, $1\,M_\odot \le M_\mathrm{1i} \le 6.3\,M_\odot$ and the onset of RLOF in the Hertzsprung gap.

3. Discussion

We calculated a binary system 4+3.6 $M_\odot$ with an initial orbital period of 3.0 days and $\delta_\mathrm{ov} = 0.12$. This binary is similar to one system in De Greve's (1993a) calculation. The results agree well with his. De Greve (1993b) made a comparison

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Table 1. Coefficients for Eqn. (4)

	$i=1$	$i=2$	$i=3$	$i=4$	$i=5$
$B_{i,1}$	2220	990.3	–403.6	2721.7	-509.6
$B_{i,2}$	–166.7	–295.1	123.3	103.5	72.8
$B_{i,3}$	107.3	158.6	–64.8	-17.5	–41.2

between the case with initial mass ratio 0.9 and the case with initial mass ratio 0.6 in Table 1 of his paper. Our calculation for low- and middle-mass binaries is similar to the result of their comparison. For binaries with initial primary mass larger than 5 $M_\odot$, there exist very large differences between our results and other authors'. For example, the hydrogen abundance at the surface of the primary is almost zero after RLOF in our binaries while about 0.2 in similar models of De Greve (1993b) and de Loore & Vanbeveren (1995). This is because that we have followed all the episodes of RLOF and they just followed the first episode (they stop primary's evolution when central helium is exhausted).

Iben & Tutukov (1985) studied numerically the evolution of close binaries with the initial masses of primary components between 3 and 12 $M_\odot$. A similarity between ours and theirs is the formation of helium-carbon-oxygen white dwarf (WD) which has a CO core surrounded by a helium shell and a very small hydrogen-rich layer. From our calculations, we find many WDs with this structure. For the primaries with initial mass of 2.5 $M_\odot$, their masses are all below $0.5 M_\odot$ when they become helium stars and finally evolve to degenerate helium-carbon-oxygen white dwarfs.

The initial–final mass relation of the present paper may be applied as an input in binary population synthesis (BPS), which has been developed recently to investigate statistical properties of stars and the formation scenarios for different types of stars (Iben, Tutukov, & Yungelson 1997; Tout, Aarseth, & Pols 1997).

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