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Influence of the Choice of Core-Envelope Transition Point on the Binary Merger of Two Main-sequence Components *

Xue-Fei Chen[1,2] and Zhan-Wen Han[1]

[1] National Astronomical Observatories, Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011; *xuefeichen717@hotmail.com*
[2] Graduate School of the Chinese Academy of Sciences, Beijing 100039

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Abstract We have studied the influence of different choices of core-envelope transition point on the final merger of contact binaries with two main-sequence components. A binary of $1.00 + 0.90\,M_{\odot}$ with an initial orbital period of 0.35 d is examined. The mass fraction of the primary mixed with the matter of the secondary, $q_{\rm mix}$, determined by the chosen core-envelope transition point, ranges from 0.04 to 1.00 in our analysis. If as $q_{\rm mix} < 0.8$, none of the helium-rich matter in the center of the primary is mixed into the envelope, and there is little distinction in the evolutionary tracks of the mergers. The timescales of the mergers remaining on the main sequence, $t_{\rm BS}$, are very similar ($\sim 6.2 \times 10^8$ yr) if $q_{\rm mix} < 0.71$, since no hydrogen-rich matter of the secondary is mixed into the core of the mergers; for $q_{\rm mix} > 0.71$, the larger $q_{\rm mix}$ is, the greater the mixing, hence the longer the blue straggler lifetime, $t_{\rm BS}$, and also the greater the luminosity. For $q_{\rm mix} = 1.00$, $t_{\rm BS} \sim 8.5 \times 10^8$ yr. Estimation by $\nabla_{\rm r} - \nabla_{\rm a} = 0.0$ shows that the point at which $t_{\rm BS}$ begins to increase is about $q_{\rm mix} = 0.68$. In comparison with the homogeneously mixed models, the merger with a helium profile similar to that of the primary is less luminous and has a shorter $t_{\rm BS}$.

Key words: stars: binaries — stars: evolution — stars: blue stragglers

1 INTRODUCTION

It has been shown by many authors that features of blue stragglers (BSs), mainly their colours and magnitudes, are important in the population synthesis of the host cluster (Landsman et al. 1998; Deng et al. 1999). The features are related to the way that the blue straggles are formed. Observations show that close binary evolution (mass transfer from a companion or coalescence of both companions) and binary-binary or binary-single collision and coalescence, play a role in some cluster BSs and field BSs (Peterson, Carney & Latham 1984; Milone & Latham 1992; Stryker 1993; Leonard 1996; Carney et al. 2001; Mapelli et al. 2004), and the

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lack of evidence for variations of radial velocities for most BSs (Stryker 1993) further indicates that binary coalescence is much more important than mass transfer in the formation of BSs. Monte-Carlo simulations show also that binary coalescence may be an important channel of forming BSs in some clusters (Collier & Jenkins 1984; Pols & Marinus 1994). However, the coalescence is very complicated and its physics is highly uncertain. The merger model can be constructed only on the basis of certain assumptions. Of these the most important one may be the choice of the core-envelope transition point that separates the core and the envelope in the primary, since it defines the chemical composition in the envelope and some of the observational characteristics, and affects the evolutionary track on the Hertzsprung-Russell diagram.

Several methods have been put forward for the determination of the core-envelope transition point, but they are for an evolved primary with a condensed core in its center (Webbink 1984; Han et al. 1994; Dewi & Tauris 2000; Tauris & Dewi 2001). For a binary which comes into contact when both components are on the main sequence, the density profile of the primary (Fig. 1), as well as the profiles of many other thermodynamic quantities (entropy, pressure and temperature, etc.), are smooth and do not have a deep gradient. In this case one cannot locate the core-envelope transition point as easily as in the case of evolved stars. Generally, different core-envelope transition points result in different evolutionary consequences. In this work, we intend to study the influence of different choices of the core-envelope transition point on the structure and evolution of the merger of a contact binary with two main-sequence components.

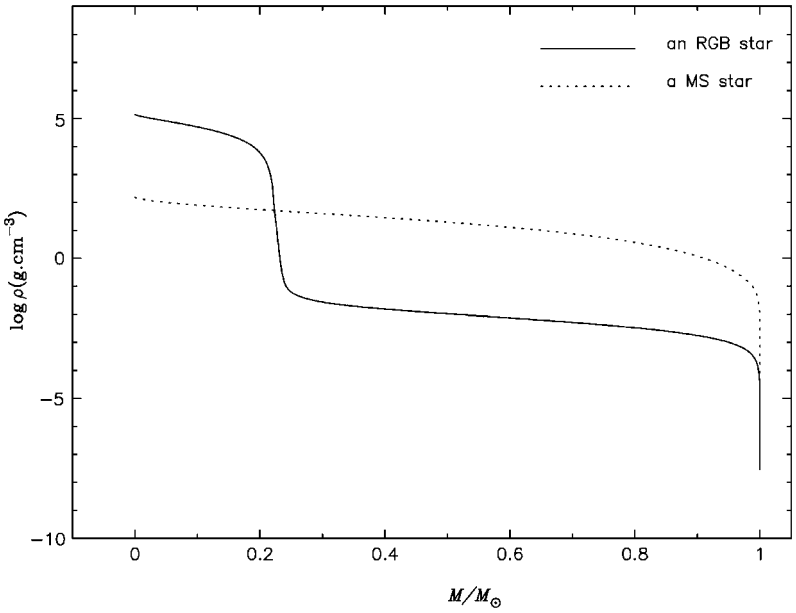

Fig. 1 Mass-density profile for a one solar mass star when on the main sequence (MS) and on the red giant branch (RGB).

2 COMPUTATIONS

We use a stellar evolution code devised by Eggleton (1971, 1972, 1973) and updated with the latest physics over the last three decades (Han et al. 1994; Pols et al. 1995; Pols et al. 1998).

Roche lobe overflow (RLOF) is included via the boundary condition

$$\mathrm{d}m/\mathrm{d}t = C \cdot \mathrm{Max}[0, (r_{\mathrm{star}}/r_{\mathrm{lobe}} - 1)^3]\,, \tag{1}$$

as we follow the evolution of the mass donor. Here $\mathrm{d}m/\mathrm{d}t$ is the mass loss rate of the primary, r_{star} is the radius of the star, r_{lobe} is the radius of its Roche lobe, and C is a constant. We take $C = 500\,M_\odot\ \mathrm{yr}^{-1}$ to make sure that RLOF can proceed steadily and the Roche lobe is just overfilled but never by too much, i.e., a transfer rate of $5 \times 10^{-7}\,M_\odot\ \mathrm{yr}^{-1}$ corresponding to an overfill of 0.1 percent. The mass-loss history of the primary, including the age when RLOF begins, the mass loss rate, and the composition of the lost matter, are stored to be used as input in subsequent calculations of the secondary.

Before the binary comes into contact, the accreting matter is assumed to be deposited onto the surface of the secondary with zero falling velocity and is distributed homogeneously all over the outer layers. The change of chemical composition on the secondary's surface caused by the accreting matter is

$$\partial X_i/\partial t = (\partial M/\partial t)/[(\partial M/\partial t)\mathrm{d}t + M_{\mathrm{s}}] \cdot (X_{i\mathrm{a}} - X_{i\mathrm{s}}), \tag{2}$$

where $\partial M/\partial t$ is the mass accretion rate, $X_{i\mathrm{a}}$ and $X_{i\mathrm{s}}$ are the abundances of species i of the accreting matter and the secondary's surface, respectively, and M_{s} is the mass of the outermost layer of the secondary. The value of M_{s} will vary with the placing of the non-Lagrangian mesh, as well as the chosen model resolution, but the variation is so small ($\sim 10^{-9} - 10^{-12}\,M_\odot$) in comparison with $(\partial M/\partial t)\mathrm{d}t$ ($\sim 10^{-3} - 10^{-5}\,M_\odot$) during the RLOF that we may ignore its effect on the element abundances. Before and after the RLOF, when no mixing occurs, we have $\partial X_{\mathrm{i}}/\partial t = 0$ from the equation (Chen & Han 2004).

We stop the calculation of the secondary when it fills its own Roche lobe at age t. The structure of the primary at t is chosen as the base pattern for the final mergers (see Sect. 3). In our calculations we assume that the system mass is conservative. Convective overshooting is ignored here as it has little effect on stars with mass less than $1.6\,M_\odot$ (Chen & Han 2003).

3 RESULTS

There are more than a dozen BSs in the old open cluster M67 and all these BSs appear to be cluster members according to their proper motions (Milone & Latham 1994). This makes M67 a good object for studying BSs. Considering that the primary mass should be a little less than the turn-off mass of M67 ($1.26\,M_\odot$) and that the choices of initial mass ratio and orbital period should ensure that the system comes into contact, when both components are on the main sequence and that the RLOF is steady before the contact, we chose a Pop I binary of $1.00 + 0.90\,M_\odot$ with an initial orbital period (P_{i}) of 0.35 d. The primary fills its Roche lobe and begins to lose mass at age 4.35×10^9 yr. The secondary expands in response to the accretion and fills its Roche lobe at age 6.68×10^9 yr, when $M_1 = 0.911\,M_\odot$ and $M_2 = 0.989\,M_\odot$. Based on the structure of M_1 at $t = 6.68 \times 10^9$ yr, we construct the merger models as follows:

First, we construct a model of $1.9\,M_\odot$ with a chemical composition similar to that of the primary within M_1 and the same as the surface of the primary in outer regions (see Fig. 2).

Secondly, different core-envelope transition points are chosen in the primary to define the chemical composition beyond the point. We assume that the matter coming from the secondary is homogeneously mixed with the matter of the primary beyond the core-envelope transition point, which is reasonable for low-mass contact binaries because the common envelope is convective in these systems (Webbink 1977). The mass fraction of the primary mixed with the

matter of the secondary is defined as $q_{\rm mix} = m_{\rm b}/M_1$, where $m_{\rm b}$ is the mass of the primary beyond the chosen core-envelope transition point. The chemical composition in the envelope of the merger is given the value,

$$X_i = (M_{i2} + M_{i1{\rm b}})/(M_2 + m_{\rm b}), \tag{3}$$

where M_{i2} and M_{i1b} denote the total masses of species i of the secondary and of the primary's envelope, respectively. We then obtain a series of models with different chemical composition distributions for different $q_{\rm mix}$.

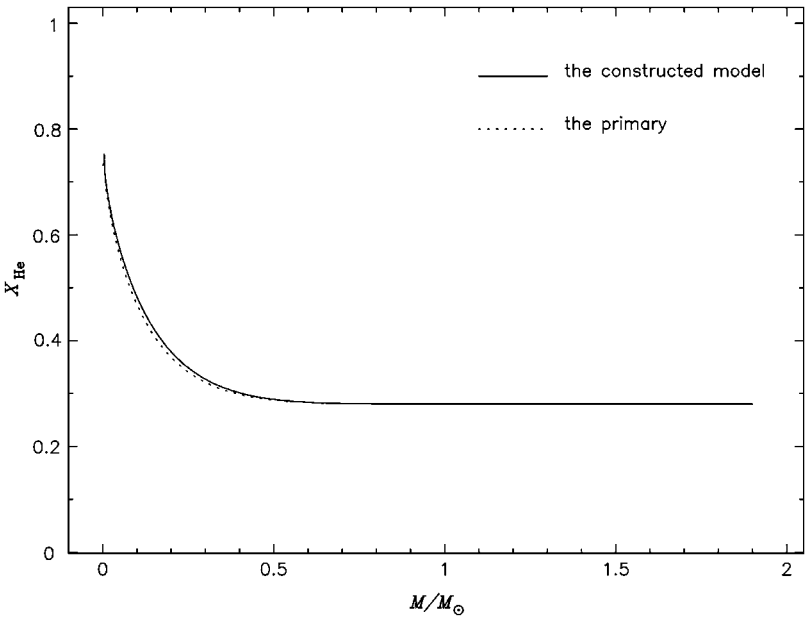

Fig. 2 Helium profiles of the primary in binary $1.00 + 0.9\,M_\odot$ at age 6.68×10^9 yr when the binary comes into contact and of the model of $1.9\,M_\odot$ to be used to construct the mergers ($q_{\rm mix} = 0.0$b in the text.).

Smoothed particle hydrodynamic (SPH) calculations show that the merger remnant of two main-sequence stars has a helium profile similar to that of the primary before collision (Lombardi, Rasio & Shapiro 1996; Sills & Lombardi 1997; Sills et al. 2001). We then construct a model of $1.9\,M_\odot$, which has a helium profile similar to that of the primary from the center to the surface (Fig. 3). The total mass of species i in the merger, M_i, is equal to $M_{i1} + M_{i2}$ in the construction of the merger, where M_{i1} is the total mass of species i of the primary. In the following descriptions we use $q_{\rm mix} = 0.0$a to represent this model while $q_{\rm mix} = 0.0$b represents the model described in the first step.

The helium profiles for all of the models are shown in Fig. 4. One can find that there is a region in which the helium abundance is less than that of the outer region for the models with $q_{\rm mix} < 0.50$. The matter in this region then has a lower mean molecular weight than that in the outer region. This results in a secular instability and thermohaline mixing (Kippenhahn, Ruschenplatt & Thomas 1980; Ulrich 1972). We include it as a diffusion process in our code (Chen & Han 2004).

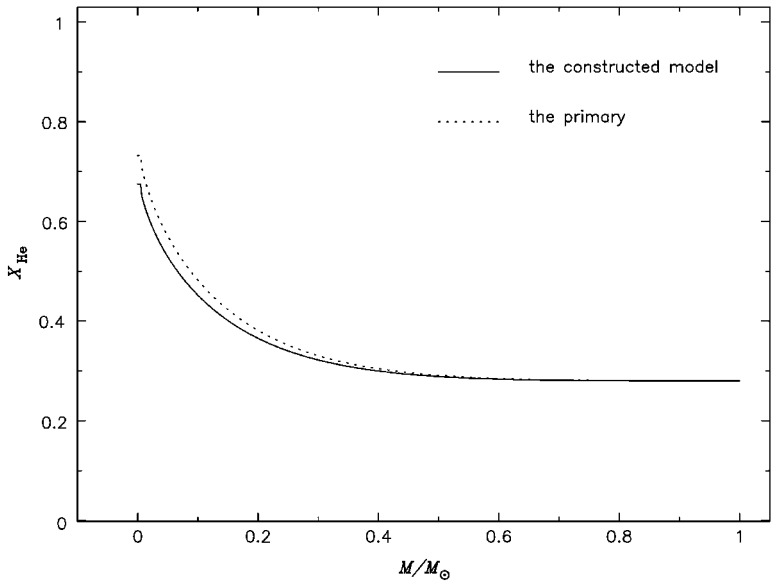

Fig. 3 Helium profiles of the primary in binary $1.00 + 0.9\,M_\odot$ at age 6.68×10^9 yr when the binary comes into contact and of the model of $1.9\,M_\odot$ which resembles the results of SPH, $q_{\rm mix} = 0.0$a in the text.

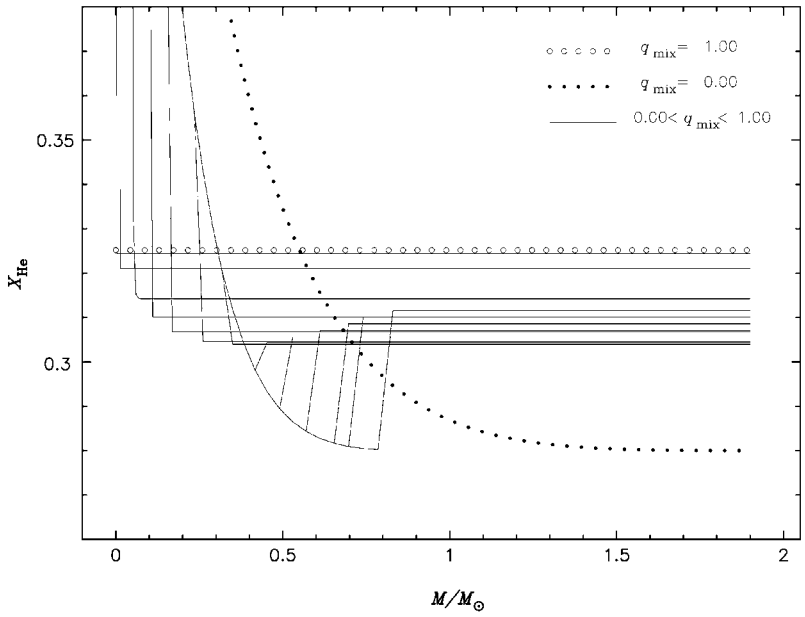

Fig. 4 Helium profiles for different core-envelope transition points. Here $q_{\rm mix}$ is the mass fraction of the primary mixed with the secondary. Note $q_{\rm mix} = 0.00$ represents the model has a helium profile similar to that of the primary when the binary comes into contact, resembling the results of SPH.

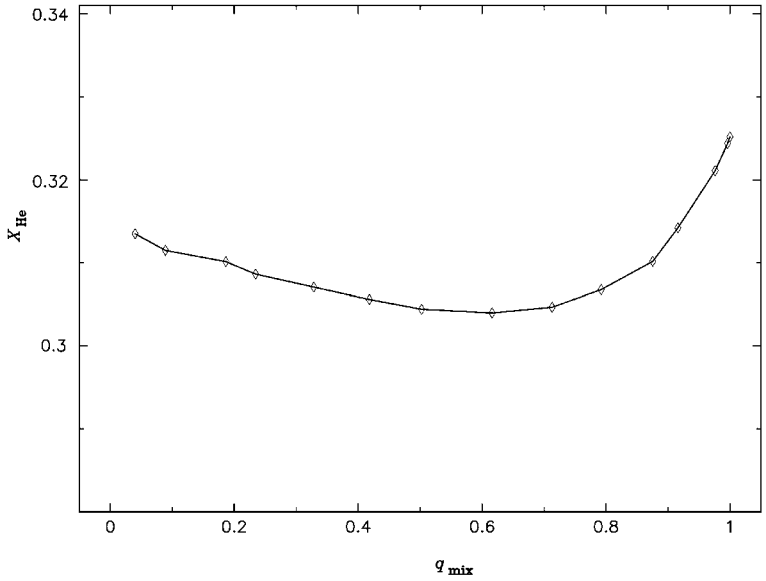

Fig. 5 Surface helium abundance for different core-envelope transition points. The result of $q_{\rm mix} = 0.00$ is not plotted as it is outside the series.

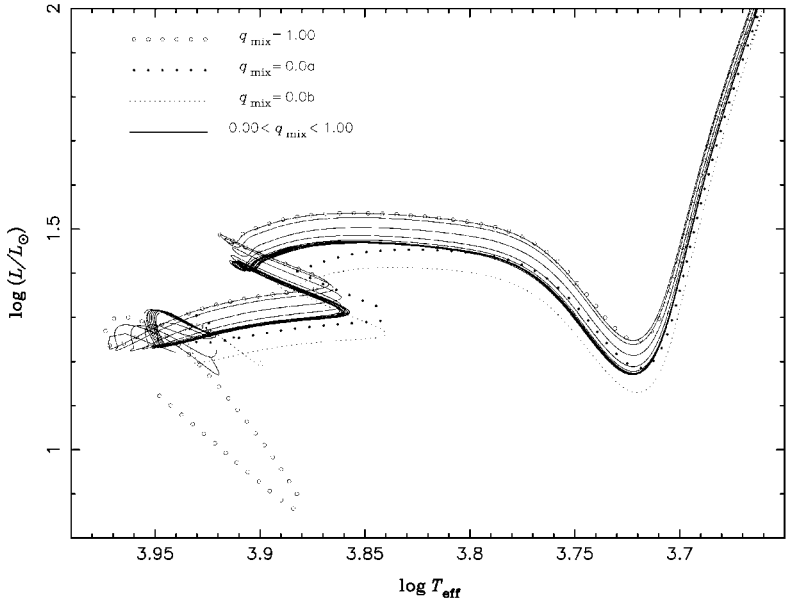

Fig. 6 Evolutionary tracks of the models on the Hertzsprung-Russell diagram. The solid lines for $q_{\rm mix} < 0.79$ overlap with each other. The distinguishable solid lines, from top to bottom, are for $q_{\rm mix} = 0.996, 0.976, 0.916$ and 0.875. Here $q_{\rm mix} = 0.0$a represents the model with a helium profile similar to the primary while $q_{\rm mix} = 0.0$b for the model we obtained at the first step in the constructing of the mergers. Self-adjustment of the models results in the irregularities at the start of the tracks.

The surface helium abundance is not monotonic with $q_{\rm mix}$ (see Fig. 5). There is a minimum value of $X_{\rm He}$ at $q_{\rm mix}$ about 0.6. When $q_{\rm mix}$ is less than 0.6, the matter of the primary beyond the core-envelope transition points is hydrogen rich compared to the matter of the secondary, then the surface helium decreases as more matter is mixed with the secondary. However, when $q_{\rm mix}$ is greater than 0.6, some helium in the center of the primary is mixed into the envelope and $X_{\rm He}$ begins to increase with $q_{\rm mix}$.

Figures 6 and 7 show the evolutionary tracks of the models on the Hertzsprung-Rusell and color-magnitude diagrams, respectively. Self-adjustment of the models results in the irregularities at the onset of the tracks. Both figures indicate little difference for models in the range $0.0 < q_{\rm mix} < 0.79$. At $q_{\rm mix} = 0.79$, a certain helium fraction in the core of the primary has already been mixed into the envelope (see Fig. 4). We therefore may ignore the effect resulting from different choices of the core-envelope transition point on the colours and magnitudes of the merger, if the core-envelope transition point is outside the nuclear reaction region of the primary.

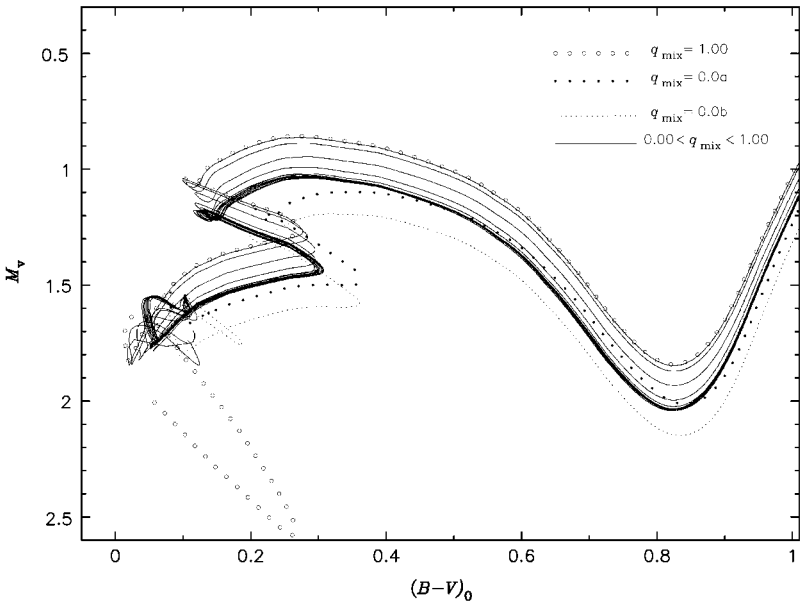

Fig. 7 Similar to Fig. 6, but for the colour-magnitude diagram.

Figure 8 shows the time-scales of the mergers remaining on the main sequence, $t_{\rm BS}$. It shows that $t_{\rm BS}$ is nearly a constant ($\sim 6.2 \times 10^8$ yr) if $q_{\rm mix} < 0.71$, because in this case no hydrogen-rich matter from the secondary is mixed into the core of the merger. However, when $q_{\rm mix} > 0.71$, a larger $q_{\rm mix}$ means more hydrogen-rich matter is mixed into the nuclear reaction region of the merger, resulting in a longer $t_{\rm BS}$.

Now we consider the case of $q_{\rm mix} = 0.00$, which represents another possible coalescence process – the binary resembles dynamic instability evolution when the loser has a deep convective envelope or the system has a large initial mass ratio ($q = M_1/M_2 \sim 3 - 4$). In these cases, RLOF may cause the core of the secondary to spiral in soon after the contact and the helium-rich matter will stay in the center of the merger (Stryker 1993). Both evolutionary tracks of

the two models, $q_{\rm mix} = 0.0$a and $q_{\rm mix} = 0.0$b, are shown in Figs. 6 and 7. Compared to the models of $q_{\rm mix} > 0.0$, both models are less luminous at a similar effective surface temperature. The $q_{\rm mix} = 0.0$a model has a shorter $t_{\rm BS}$ ($\sim 5.6 \times 10^8$ yr) than the $q_{\rm mix} > 0.0$ model, while the $t_{\rm BS}$ of the $q_{\rm mix} = 0.0$b model ($\sim 6.6 \times 10^8$ yr) is a little longer than those in the range $0.00 < q_{\rm mix} < 0.71$.

In fact, we may define the point at which $t_{\rm BS}$ begins to obviously increase by the condition $\nabla_{\rm r} - \nabla_{\rm a} = 0.0$ from the model of $q_{\rm mix} = 0.0$b, since the central convective region will develop through self-adjustment only when $\nabla_{\rm r} > \nabla_{\rm a}$. In Fig. 9 we show the profiles of ∇, $\nabla_{\rm a}$ and the hydrogen mass fraction for $q_{\rm mix} = 0.0$b. We see that the point at which ($\nabla < \nabla_{\rm a}$) is at mass $M_{\rm i}$ about $0.29\,M_\odot$, corresponding to $q_{\rm mixc} = (M_1 - M_{\rm i})/M_1 = 0.68$. It means that for $q_{\rm mix} < 0.68$, the change in the chemical composition of the envelope has little effect on the element abundances in the central convective region as the model reaches thermal equilibrium. However, the composition in the envelope will affect the distribution of temperature, hence the nuclear reaction rate, and finally $t_{\rm BS}$. In comparison with the mergers within $0.0 < q_{\rm mix} < 0.68$, the model of $q_{\rm mix} = 0.0$b has a similar hydrogen mass fraction in the central convective region and a lower temperature at the same mass, so has a longer $t_{\rm BS}$.

4 DISCUSSION AND CONCLUSIONS

The influence of different choices of the core-envelope transition point on the final mergers of contact binaries with two main-sequence components has been investigated, and a binary of $1.00{+}0.90\,M_\odot$ with an initial orbital period of 0.35 d has been examined, based on the following assumptions: (a) contact binaries with two main-sequence components eventually coalesce; (b) the matter of the secondary is homogeneously mixed with that of the primary beyond the core-envelope transition point; (c) the mass of the system is conservative. Before coming to our conclusions, we present a brief discussion on these assumptions.

Webbink (1976) studied the evolutionary fate of low-mass contact binaries, and found that a system cannot sustain its binary character beyond the limits set by marginal contact evolution ($\mu = M_1/(M_1 + M_2) = 1.0$). As he noted in that paper, the primary in a real system may accommodate the entire angular momentum of the system much earlier than the time given by marginal contact evolution. Meanwhile, the coalescence may be accelerated by the loss of angular momentum which is unavoidable when the system passes through the common envelope phase during the coalescence. He therefore argued that a contact binary will very likely coalesce while the primary is still on the main sequence. Nelson & Eggleton (2001) undertook a complete survey of case A binary evolution. They defined six subtypes of case A evolution and three of these (AD, AR and AS) lead to contact when both components are on the main sequence (see also Eggleton (2000)). Case AD, with dynamic-timescale RLOF and where either the loser has a deep convective envelope or the system has a large initial mass ratio, very probably leads to common envelope, spiral-in, and coalescence on a quite short timescale. The final consequences of AS and AR are not very clear, but Eggleton (2000) pointed out that systems undergoing the AR or AS evolution may maintain a shallow contact (perhaps intermittently) as the mass ratio becomes more extreme, and eventually coalesce. In fact, whether the system is merged or not is related to the binding energy of the envelope, hence to the choice of the core-envelope transition point in the primary. We will study the consequences in detail in another paper.

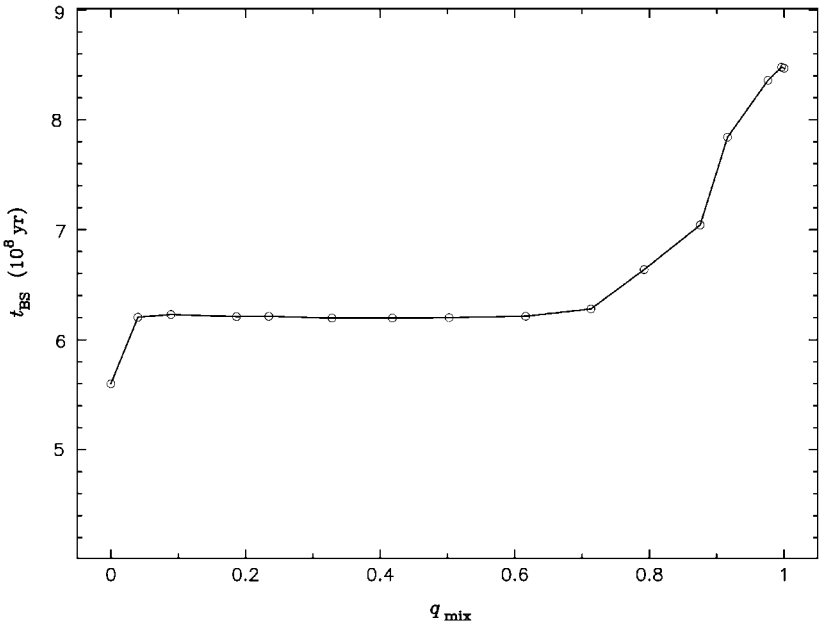

Fig. 8 Lifetimes of the mergers remaining on the main sequence for different core-envelope transition points.

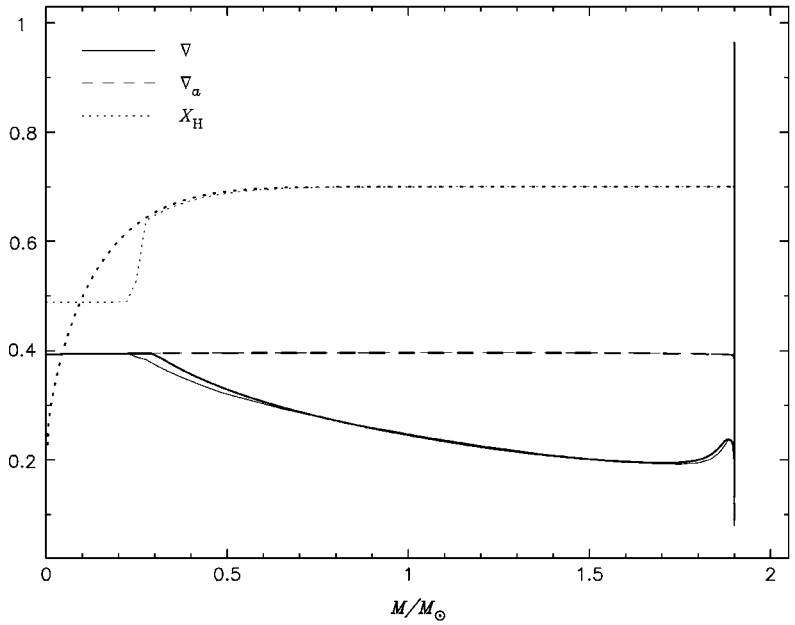

Fig. 9 Profiles of ∇, $\nabla_{\rm a}$ and hydrogen mass fraction for $q_{\rm mix} = 0.0$b. The thick lines are for the model before self-adjustment while the thin ones are for the model at thermal equilibrium after some adjustment.

For low-mass contact binaries, the common envelope is convective (Webbink 1977), the matter in it then is homogeneous. If the system mimics shallow contact during coalescence, it is reasonable that we assume the matter of the secondary mixes with the envelope homogeneously. If the core of the secondary spirals in very quickly, i.e., case AD evolution, the matter in the core of the secondary will stay in the core of the merger (Stryker 1993). The merger then has a chemical composition distribution similar to that of the primary, i.e., the helium distribution decreases monotonically from center to surface. Similarly, if the matter from the secondary does not mix homogeneously with the envelope of the primary (e.g., if the common envelope is radiative during the W UMa phase), one may simply see the consequences as follows – an extremum may appear in the helium profile where the secondary disintegrates, but the extremum will disappear soon because of thermohaline mixing taking effect in this region. Different from the homogeneously mixed models, little helium-rich matter of the secondary will be carried onto the surface in this case. If the core-envelope transition point is close enough to the center, then the extremum does not appear in the helium profile of the merger, i.e., the helium mass fraction is greater within the core-envelope transition point than at the center of the secondary and the helium profile will be very close to that of $q_{\rm mix} = 0.0$a. Thus, both case AD evolution and inhomogeneously mixed assumption lead the merger very similar to the one with $q_{\rm mix} = 0.0$a with a similar helium profile to that of the primary.

The timescale for the binary components from contact to coalescence is an important parameter here, because if it is too long, the structures of both components will change greatly or the system may have not completed the coalescence. Previous studies (van't Veer 1994; Dryomova & Svechnikov 2002) showed that the timescale is about 5×10^8 yr, which is much shorter than the lives of both components of low-mass binaries. So we may ignore the changes of structures of the individual components during the merging. van't Veer (1997) found from observations that the mass loss from the system during coalescence is at a rate about $10^{-10}\,M_\odot{\rm yr}^{-1}$. If we consider that the coalescence takes 5×10^8 yr in a binary, only $0.05\,M_\odot$ is lost from the system as the binary finally becomes a single star. Hence, as a good approximation, we can assume mass conservation during coalescence.

The SPH simulations of Benz & Hills (1987) showed that BSs produced by collisions are initially full mixed (the case $q_{\rm mix} = 1.00$ in the present paper). Though the subsequent calculations (Lombardi, Rasio & Shapiro 1996; Sills & Lombardi 1997; Sills et al. 2001) led to the different conclusion that the collision products are not mixed, the comparison of theoretical calculation with the brightest BSs in NGC 6397 by Sills, Bailyn & Demaroue (1995) indicated that a fully mixed model may fit the observations better than the unmixed model (the mixing probably happens after the collision, i.e., during the adjustment of the merger from dynamical equilibrium to thermal equilibrium). Meanwhile, Ouellette & Pritchet (1996) also showed that a fully mixed model may give a better fit to the BSs in the outer regions of M3 than the unmixed model. In fact, the two components of a contact binary might disintegrate instantaneously if they are very similar in structure and compactness. The adjustment of the merger then resembles the pre-main-sequences evolution, resulting in a homogeneous distribution of chemical composition in the whole star. Therefore, the fully mixed model may be an appropriate assumption for some BSs. However, the scattered colour distribution of low-luminosity BSs in NGC 6397 cannot be explained by the fully mixed model, which predicts a definite concentration of stragglers toward the blue side of the region (Sandquist, Bolte & Hernquist 1997). It is possible that both of these models exist in a same cluster. Present observations and theoretical calculations cannot rule out any values of $q_{\rm mix}$.

In this paper we have studied the influences of different core-envelope transition points

on the final mergers by case A binary evolution. The results indicate little differences in the evolutionary tracks, or in the colours, magnitudes and timescales on the main sequence of the mergers, if hydrogen-rich matter from the secondary does not mix into the nuclear reaction region of the mergers, i.e., if $q_{\rm mix} < 0.71$. For $q_{\rm mix} > 0.71$, a larger $q_{\rm mix}$ leads to a greater mixing of hydrogen-rich matter into the nuclear reaction region of the merger, hence a longer $t_{\rm BS}$, as well as a higher luminosity. The point at which $t_{\rm BS}$ begins to increase can be defined by $\nabla_{\rm r} - \nabla_{\rm a} = 0.0$ in the base pattern ($q_{\rm mix} = 0.0$b) we used to construct the mergers. For the binary $1.00 + 0.9\,M_{\odot}$ with $P_{\rm i} = 0.35$ d, this definition gives $q_{\rm mix} = 0.68$. In comparison with the homogeneously mixed models, the merger with a helium profile similar to that of the primary ($q_{\rm mix} = 0.0$a) is less luminous and has a shorter $t_{\rm BS}$.

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