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Modeling blue stragglers in young clusters*

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Abstract A grid of binary evolution models are calculated for the study of a blue straggler (BS) population in intermediate age ($\log \mathrm{Age} = 7.85 - 8.95$) star clusters. The BS formation via mass transfer and merging is studied systematically using our models. Both Case A and B close binary evolutionary tracks are calculated for a large range of parameters. The results show that BSs formed via Case B are generally bluer and even more luminous than those produced by Case A. Furthermore, the larger range in orbital separations of Case B models provides a probability of producing more BSs than in Case A. Based on the grid of models, several Monte-Carlo simulations of BS populations in the clusters in the age range are carried out. The results show that BSs formed via different channels populate different areas in the color magnitude diagram (CMD). The locations of BSs in CMD for a number of clusters are compared to our simulations as well. In order to investigate the influence of mass transfer efficiency in the models and simulations, a set of models is also calculated by implementing a constant mass transfer efficiency, $\beta = 0.5$, during Roche lobe overflow (Case A binary evolution excluded). The result shows BSs can be formed via mass transfer at any given age in both cases. However, the distributions of the BS populations on CMD are different.

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

1 INTRODUCTION

Blue stragglers (BSs) are observed in almost all stellar systems which appear to be anomalously young compared to other populations in the system. They are commonly defined as stars that are brighter and bluer than the turn-off (TO) point on the color magnitude diagram (CMD). Such stars seem to remain on the main sequence (MS) longer than is estimated by the standard theory of stellar evolution. The existence of BSs can significantly affect the integrated spectral energy distributions, especially in the blue and UV bands (Li & Han 2009; Xin et al. 2007), thus challenging the traditional model of a single stellar population (SSP) model.

Ferraro et al. (1993) found two groups of BSs in M3, which have a bimodal radial distribution. They concluded that either the two groups of BSs have different physical properties or they represent the products of different formation mechanisms. Laget et al. (1994) identified 24 BSs in a UV

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imaging study of M3. They found two distinct classes of BSs in M3. One has a normal UV flux distribution and may be the massive stars formed through stellar collisions, whereas the other has UV excess and appears to be composite systems consisting of a hot secondary star orbiting an MS turn-off star or a subgiant or even possibly a low luminosity giant. Recently, Ferraro et al. (2009) observed two distinct sequences of BS populations on the CMD of M30. They concluded that the bluer sequence is arising from direct collisions and the redder one is arising from the evolution of close binaries possibly still experiencing mass exchange. All the observations above suggest that BSs may have different formation mechanisms.

Though BS formation mechanisms are not completely understood yet, many possible scenarios have now been proposed to explain BS formation (see the review of Stryker 1993). At present, some possible ways are believed to account for the BS formation: mass transfer or complete coalescence in close binaries, and stellar mergers resulting from direct collisions. It is believed that more than one scenario is necessary to explain the observations. However, the relative importance of the two possible mechanisms remains unclear.

The mechanism of mass transfer in close binaries was first proposed by McCrea (1964). Mass transfer can occur when the massive component in the binary system expands out of the Roche lobe. As a result of mass transfer, the companion can become a more massive MS star than TO stars whose life time could be notably extended, or even doubled compared to a star with the same final mass. Coalescence of the two components may also occur during the process. Three mass transfer cases (Case A, Case B and Case C) are defined according to the evolutionary state of the primary at the onset of mass transfer. They are associated with the evolutionary stages respectively: Case A on the MS, Case B after the MS before helium ignition and Case C during central He-burning and afterwards (Kippenhahn & Weigert 1967). The mass of BSs formed this way cannot exceed twice the cluster turn-off mass. In addition to BSs, many other observational objects are also associated with interactive binaries, such as Ba stars which can be explained by mass transfer through wind accretion, disk accretion or common envelope ejection (Liu et al. 2009). Binary interactions are sometimes linked to variable stars observed in star clusters. It is known that some cluster variable stars are still in binary systems, such as symbiotic stars, W UMa stars and EA-type binaries. A series of works searching for variables in clusters has been performed up to now (Lü et al. 2006, 2007; Xin et al. 2002; Zhang et al. 2003, 2005 Li et al. 2004Li et al. 2004bLi et al. 2004a). Moreover, binaries (a white dwarf + an MS or red giant) are believed to be possible progenitors of type Ia supernovae (Meng et al. 2006, 2009; Wang et al. 2008, 2010; Wang & Han 2010a,b; Guo et al. 2008).

BSs could also, in principle, be formed in direct collisions between MS stars. The direct collision hypothesis was originally presented by Hills & Day (1976). They proposed that the remnant of two MS stars after collision could also produce a BS. This is likely to be the cause of BSs that form in globular clusters, where star densities are extremely high and dynamical effects are thought to play a dominant role. However, it is unlikely to happen for open clusters, as the time-scale of collision is too long (Press & Teukolsky 1977; Mardling & Aarseth 2001) and neither the peculiar compositions of Ap and Bp-type BSs, nor different rotation rates of observed BSs are by themselves sufficient to explain the large color differences between observed BSs and MS stars (Mermilliod 1982).

Different mechanisms are believed to be dominant in different environments. As a consequence of dynamic evolution of the host cluster, the collision scenario is thought to be responsible for BSs in dense cluster cores. Binary interaction processes and products are believed to dominate in more sparse environments such as open clusters and in the field (Mapelli et al. 2004; Lanzoni et al. 2007; Dalessandro et al. 2008; Sollima et al. 2008).

Many detailed works about these two mechanisms have been presented. Pols & Marinus (1994) performed Monte-Carlo simulations of close binary evolution in young clusters. The BSs predicted by their work agree well with the observations quantitatively for clusters younger than about 300 Myr but are not enough for the clusters with older ages (between 300 and 1500 Myr). N-body simulations of BSs in the old open cluster M67 (Hurley et al. 2001, 2005) suggest that the formation of BSs is dominated by both mass transfer and cluster dynamics.

Recently, the binary explanation was claimed to be dominant even in dense globular cluster cores (Knigge et al. 2009). They found a clear, but sub-linear correlation between the number of BSs in a cluster core and the total stellar mass contained within it. It is regarded as the strongest and most direct evidence to date that most blue stragglers, even those found in cluster cores, are the progeny of binary systems.

Some other mechanisms can also contribute to a BS population. BSs predicted in the mass transfer theory are fainter than 2.5 mag above the cluster TO stars, but there are exceptions in observations such as F81 in M67. To explain these massive stragglers, Perets et al. (2009) discussed the possibility for BS formation in primordial and/or dynamical hierarchical triple stars. Chen & Han (2008) estimated the remnants of binary coalescence from Case A models. The resulting BSs in their work are also able to predict some highly luminous BSs, however, the small quantity can hardly match the luminous BSs in M67. Angular momentum loss (AML) in low mass binaries can also contribute to BS populations, but only in old clusters. There are a number of subjects including the treatment of AML (Li et al. 2004; Li et al. 2004a, Demircan et al. 2006; Politano & Weiler 2006; Stepien 2006). The recent study of Chen & Han (2008, 2009)) also demonstrated that AML is likely a main factor of BS formation in old open clusters. However, its contribution can be ignored in clusters younger than 1.0 Gyr.

It is more difficult to study BSs in young clusters than in old ones in a systematic manner, as the observed BSs in younger clusters are usually very limited due to the relatively small number of massive MS stars. We investigated Case A mass transfer in close binaries in young clusters NGC 1831, whose log(age) is around 8.65 by isochrone fitting. The result shows that binaries experiencing Case A mass transfer can hardly account for the luminous BSs in such young clusters (Lu & Deng 2008). A subsequent work which combined Cases A and B was then performed to study BSs in old open clusters. The evolutionary behaviors of Cases A and B were compared in detail. We concluded that Case B is as important as Case A in old clusters, and it is even more important in younger clusters by comparing the different evolutionary behaviors with different initial primary masses. We predicted that BSs formed via Case B mass transfer can be brighter and bluer than Case A, and the number of BSs can be remarkably larger (Lu et al. 2010, hereafter LDZ10) thus providing a clue for studying the statistics of BSs in such young clusters.

In this work, we apply the same approach as in LDZ10 to systematically study BS populations in younger stellar populations represented by open clusters. We select clusters younger than 1.0 Gyr in this paper, because stellar densities in young clusters are sufficiently low that dynamical effects are not so important and they do not complicate our study. Furthermore, there is good evidence for the presence of a significant fraction of primordial binaries in such young clusters, making it not only interesting but also essential to better understand the evolution of the cluster. A large grid of binary evolutionary calculations with the initial mass of the donor ranging from 2.0–7.6 $M_\odot$ are carried out in this work. The models can cover all close binaries experiencing mass transfer between 70.0 Myr and 1.0 Gyr.

We describe and analyze our models in Section 2. Several Monte-Carlo simulations are presented and the results are shown in Section 3. We will discuss the specific frequency of $N_{\rm BS}/N_2$ in our simulations and compare our results to the observations in Section 4. Summaries and conclusions are given in the final section.

2 THE BINARY MODELS

We use the stellar evolutionary code of Eggleton (1971, 1972, 1973) which was updated by Han et al. (1994, 2000) and Pols et al. (1995, 1998) to compute close primordial binary evolutionary models instead of using analytic formulae to approximate the main characteristics of stellar evolution. Some intrinsic stellar parameters need to be taken care of because they have close relationships with unsolved problems in the theory of stellar structure and evolution, especially for massive stars (Deng & Xiong 2001; Tian et al. 2009). Eggleton's code can provide more detailed information on the evolution of close binaries. The code uses the radiative opacity library from Iglesias & Rogers (1996) and molecular opacities of Alexander & Ferguson (1994). Roche lobe overflow (RLOF) is treated as a boundary condition within the code. The accreted material from the primary is assumed to be simply deposited on the surface of the secondary and instantly distributed homogeneously over the outer layers.

We consider two main mechanisms of BS formation in this work which mainly depend on the initial mass ratio. During RLOF, the secondary may accrete material transferred from the primary or merge with the primary depending on the initial mass ratio $q(M_2/M_1)$. With a small $q < q_{\rm crit}$, RLOF is dynamically unstable and the secondary quickly fills its Roche lobe at the onset of mass transfer. A common envelope (CE) is formed afterward. The CE may be ejected depending on its binding energy or the binary will merge. The remnant could be a BS if both companions are MS stars. The merging process is complicated and the physics during the process is still uncertain. The composition of the mergers may influence their lifetimes on the MS and their positions on CMD, whereas the fully mixed model is an extreme case. Any alternative will lead to a shorter MS lifetime. We constructed the merger models by assuming that all the low q mergers are fully mixed and possess the corresponding binary mass. With a larger $q > q_{\rm crit}$, RLOF is quite stable and can be calculated by Eggleton's code. If the secondary is a MS star, the luminosity will go upward along the MS as a result of mass accretion. Whether it could become a BS or not depends on the final mass when RLOF terminates. For some Case A models, the system may make contact during RLOF because of the small initial space orbital separation. Previous studies indicate that a contact binary will eventually coalesce (Webbink 1976; Eggleton 2000; Li et al. 2005), although there are still some debates over the coalescence time-scale (Eggen & Iben 1989; Van'T Veer 1994; Dryomova & Svechnikov 2002; Bilir et al. 2005). The remnants of binary coalescence could contribute to luminous BSs, however their number is too limited to make a notable influence on the statistical property of clusters (Chen & Han 2009). The number of this case in our model is also very limited so we just terminate the code when the two components come into contact. We are unable to follow the RLOF that begins during the red giant branch (RGB) due to some numerical problems. Finally, we calculate a series of close binary evolutionary models covering Case A and part of Case B (RLOF during the Hertzsprung gap (HG)) with the initial primary mass M_1 = 2.0 – 7.6 $M_\odot$ and solar metallicity. The interval of M_1 is 0.1 $M_\odot$ when $M_1 < 6.0\,M_\odot$ and 0.2 $M_\odot$ when $6.0\,M_\odot < M_1 < 7.6\,M_\odot$. The initial mass ratios M_2/M_1 are from 0.2 to 0.9 with an increment of 0.1. The initial orbital separations are from 5.0 $R_\odot$ to 320.0 $R_\odot$ with an increment of 2.0 $R_\odot$ for most of our models and 4.0 $R_\odot$ only when $M_1 > 5.0M_\odot$ and $R_{\rm initial} > 40.0\,R_\odot$. More details about the modeling of the evolutionary models and the configurations of the code have been discussed in LDZ10.

Figure 1 shows the evolutionary tracks of two close binary systems ($3.5\,M_\odot + 2.0\,M_\odot$). On the left panel the initial orbit is $13.0\,R_\odot$ so it follows the Case A mass transfer while the other two have orbital separations that are doubled and are experiencing Case B mass transfer (the middle and the right panel). Different mass transfer rates are set in both Case B plots and this issue will be discussed in the next paragraph. Solar composition ($Z = 0.020$, $Y = 0.280$) is adopted in the models. The mass transfer begins when the primary overfills its Roche lobe at the MS for Case A (the left panel) and the HG for Case B (the middle and the right panel), and slows down as the primaries evolve to the bottom of the RGB in both models. The mass ratio quickly reverses when reaching the bottom of the RGB. As a result of mass accretion, the luminosity of the secondaries evolves upward along the main sequence in CMD as shown by the solid lines on all the plots. After the termination of mass transfer, the accretors in the models follow the regular evolutionary paths of single stars with about 90 percent of the total system mass. The previous mass donors become C-O dwarfs with $\sim 0.44\,M_\odot$ in the first case (Case A mass transfer) and $\sim 0.58\,M_\odot$ in the second one (Case B mass transfer).

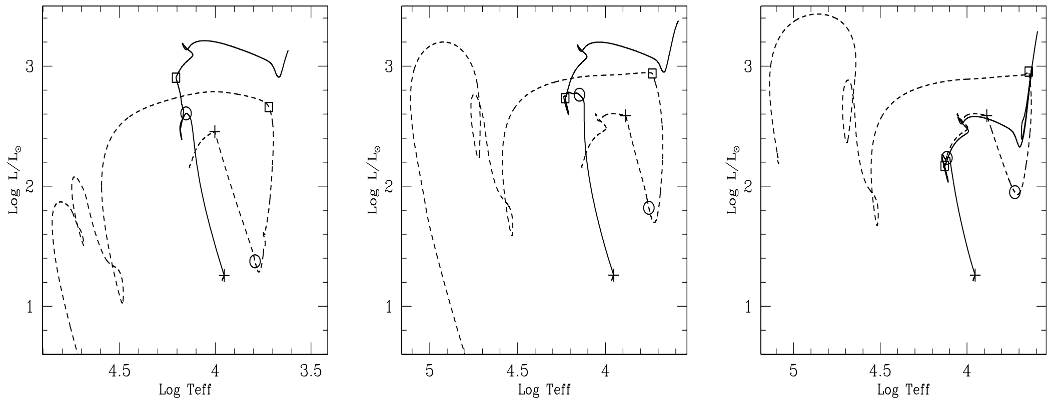

Fig. 1 Evolutionary tracks of two components ($3.5+2.0M_{\odot}$) undergoing Case A (the *left* panel) and Case B scenarios ($\beta = 100\%$ for the middle panel and $\beta = 50\%$ for the *right* panel). The dashed and solid lines are the evolutionary tracks of the primary and the secondary respectively. The plus signs, open circles and open squares show their positions, in order, when the mass transfer begins; the mass ratio equals one, and the mass transfer terminates.

Conservations in both mass and angular momentum are assumed for Case A and Case B. However, the assumption is only reasonable for a restricted range of intermediate-mass binaries as predicted by Nelson & Eggleton (2001). The efficiency of mass transfer, β, which is defined as the mass fraction of the matter accreted by the secondary to that lost from the primary, is one of the major uncertainties in the evolutionary calculations of close binaries. In general, the factor of β could influence the final mass of the secondary after RLOF. Many relevant processes are still not yet well understood and the value is therefore unclear. Obviously, with a larger β, the companion could accrete more material and become more massive and therefore more luminous. However, the lifetime of the secondary on the MS after RLOF decreases along with the increasing final mass. The larger β is, the shorter the time it remains on the MS. Usually a high value is suggested for the mass donor on MS or HG and a low value for the mass donor on the first giant branch (FGB) or asymptotic giant branch (AGB). de Mink et al. (2007) presented 20 000 detailed evolution models to fit a sample of 50 double-lined eclipsing binaries in the Small Magellanic Cloud. They found no single value of β that can explain all the systems. In many calculations of binary evolution, usually a single constant mass transfer efficiency of 0.5 has been assumed (e.g. De Greve & De Loore 1992; Chen & Han 2002, 2009). In order to investigate the non-conservative case which is more likely in reality, we consider such an effect by using a constant mass transfer for efficiency. The right panel in Figure 1 is an example. Due to the mass loss from the system during RLOF, the luminosity of the accretor cannot reach as high as the conservative case on the Hertzprung-Russell diagram. A separate set of non-conservative models is calculated using the same parameter set, the results of which will be discussed in Section 3.

The time of the on-set of mass transfer is critical for the subsequent evolution as shown in our previous study (LDZ10). Our study shows that the duration and luminosity of close binary systems during and after mass transfer vary greatly.

Figure 2 shows the synthetic colors of the system with respect to those of the turn-off of the corresponding isochrones at the same age as a function of age. The initial parameters of the systems in the figure are: $M_1 = 3.5\,M_{\odot}$, $M_2 = 2.0\,M_{\odot}$ and five different initial orbital separations of 10, 12, 14, 16 and 20 $R_{\odot}$. The conservative cases are shown on the left panel and the non-conservative cases

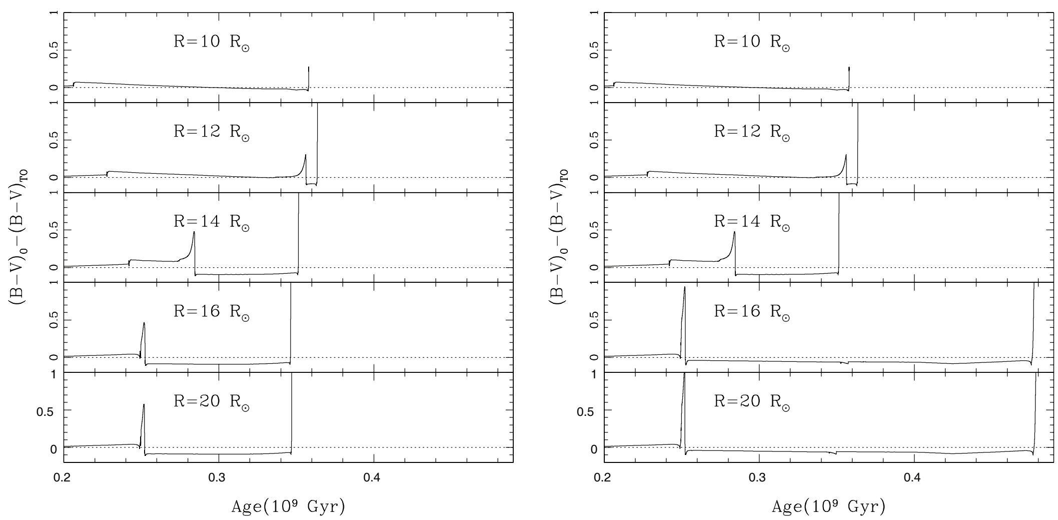

Fig. 2 Evolution of synthetic color, for example models with $M_1 = 3.5\,M_\odot$, $M_2 = 2.0\,M_\odot$ at five different orbital separations. Case B models on the left panel are for $\beta = 1$ while those on the right panel are for $\beta = 0.5$. The dotted lines indicate $(B-V)_0 - (B-V)_{\rm TO} = 0$.

are shown on the right panel. The upper three rows in both plots are Case A models and the bottom two are Case B models. The dotted lines ($(B-V)_0 - (B-V)_{\rm TO} = 0$) are the location of the TO point at different ages. The portions of the solid lines below the dotted lines are the BS phase. We can notice clearly that the durations of binary models being in the BS phase region become longer while the initial orbital separation increases; and Case B makes the evolution of the binary systems much longer in the BS phase than in Case A and even longer in the non-conservative case as shown in the bottom two rows on the right panel. The evolutionary behaviors of Case B models are similar when $R_{\rm initial} > 16\,R_\odot$. We can also notice that BSs formed via Case B seem brighter and bluer than those formed via Case A. This behavior is similar to binary systems with lower masses as in LDZ10.

3 MONTE-CARLO SIMULATIONS

It is possible to investigate the statistical properties of the BS population from mass transfers and mergers based on our models. We have tested a detailed method in a previous work that simulated the BS population in old clusters such as M67. In this work, we would like to extend the algorithm to cover younger clusters and make it possible to compare our theoretical models of BS populations to observations (Ahumada & Lapasset 2007, hereafter AL07). We performed a series of Monte-Carlo simulations for a large sample of 10^6 binaries. A single starburst is assumed in our calculation. For simplicity, the initial mass function (IMF) of the primary, the initial mass ratio distribution and the distribution of initial orbital separations are the same as in our previous studies. They are also described as follows.

(1) The IMF of Kroupa et al. (1991), which reproduces a distribution of masses similar to the best fits of KTG, is adopted. It agrees well in the $U-B$ and $B-V$ colors with the traditional way of constructing the IMF of KTG93 on SSPs (Zhang et al. 2005). It is convenient to use in Monte-Carlo simulations and the initial mass of the binaries can be given by the generating

function.

$$M(X) = 0.33 \left[\frac{1}{(1-X)^{0.75} + 0.04(1-X)^{0.25}} - \frac{(1-X)^2}{1.04} \right], \tag{1}$$

where X is a random number uniformly distributed between 0 and 1. $M(X)$ is the binary mass in units of $M_\odot$. $M(X)$ is limited between 0.2 and 100.0 $M_\odot$ by the assumption of a single-star population covering 0.1 to 50.0 $M_\odot$.

(2) We adopt a uniform distribution of mass ratio as given by Hurley et al. (2001),

$$1 > q > \mathrm{Max} \left[\frac{0.1}{M(X) - 0.1}, 0.02(M(X) - 50.0) \right]. \tag{2}$$

(3) We assume that the distribution of separations is constant in $\log \alpha$ (α is the orbital separation) from Pols & Marinus (1994). The lower limit of separation is where a zero age main sequence (ZAMS) star fills its Roche lobe and the upper limit adopted here is 50 AU (Hurley et al. 2005).

4 RESULTS AND DISCUSSION

The current $M_{\rm V}$ and $(B-V)_0$ of any close binaries whose initial parameters are in the range of our grid can be obtained by linear interpolation. The simulation space has three degrees of freedom: orbital separation, mass ratio and donor mass. The parameters are defined in a huge table (available online). Table 1[1] is a truncated version for demonstration.

Table 1 Models of Case A, Case B and mergers. Only a sample of the table is included here. The full table is available in electronic form.

log (age) (yr)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	α ($R_\odot$)	V	$B-V$	β
8.25	4.5	2.7	10.0	−2.241	−0.116	1.0
8.25	4.5	2.7	12.0	−2.161	−0.108	1.0
8.25	4.5	2.7	14.0	−2.113	−0.194	1.0
8.25	4.5	2.7	16.0	−2.349	−0.185	1.0
8.25	4.5	2.7	18.0	−2.431	−0.180	1.0
8.25	4.5	2.7	20.0	−2.425	−0.180	1.0
8.25	4.5	2.7	22.0	−2.415	−0.180	1.0
8.25	4.5	2.7	24.0	−2.407	−0.180	1.0
8.25	4.5	2.7	26.0	−2.400	−0.180	1.0
8.25	4.5	2.7	28.0	−2.394	−0.181	1.0
8.25	4.5	2.7	30.0	−2.387	−0.181	1.0
8.25	4.5	2.7	32.0	−2.382	−0.181	1.0
8.25	4.5	2.7	34.0	−2.377	−0.181	1.0
8.25	4.5	2.7	36.0	−2.374	−0.181	1.0
8.25	4.5	2.7	38.0	−2.369	−0.181	1.0
8.25	4.5	2.7	40.0	−2.366	−0.181	1.0
8.25	4.5	2.7	42.0	−2.364	−0.181	1.0
...	...	...	...	...	...	...

Notes: The columns of this table mean the age, the mass of the donor(M_1) and its companion(M_2), the orbital separation, magnitude in V band, the color of $B-V$ and the mass transfer efficiency.

A sample of clusters in AL07 is selected based on age and metallicity in order to check our simulations. The fundamental parameters of these selected clusters are listed in Table 2. In order to facilitate the comparison, first we need to pay attention to the identification criterion of BSs in

[1] The complete table and the evolutionary tracks of all the models are only available in electronic form via *http://sss.bao.ac.cn/BS-model2/*

Table 2 Parameters of Young Clusters with Metallicity Similar to the Sun ($Z = 0.02$)

Cluster Name (1)	$\log(t)$ (yr) (2)	$E(B-V)$ (3)	DM (4)	Z (5)	[Fe/H] (6)	N_2 (7)	$N_{\rm BS}$ (8)	f (9)	References (10)
NGC 2516	8.15	0.12	7.93	0.018	−0.05	40(35)	1(6)	0.025(0.171)	[1,2]
NGC 5316	8.20	0.27	11.26	0.019	−0.02	10(20)	0(4)	0.000(0.200)	[1,4,6]
IC 2488	8.25	0.24	11.20	0.019	−0.02	30(10)	3(1)	0.100(0.100)	[1,17]
NGC 1545	8.45	0.30	10.19	0.017	−0.06	10(20)	0(1)	0.000(0.050)	[1,4,6]
NGC 6281	8.50	0.15	8.93	0.02	0.00	20(25)	0(4)	0.000(0.160)	[1,4,6]
IC 2714	8.50	0.36	11.68	0.015	−0.12	110(80)	2(1)	0.018(0.013)	[1,14]
NGC 1027	8.55	0.33	10.46	0.023	0.06	40(40)	0(2)	0.000(0.050)	[1,4,5]
Melotte 111	8.60	0.00	4.77	0.019	−0.03	10(10)	1(1)	0.100(0.100)	[1,8]
NGC 1245	8.70	0.30	12.27	0.018	−0.05	160(75)	7(9)	0.044(0.120)	[1,9,10]
NGC 6633	8.80	0.17	7.80	0.015	−0.11	40(40)	4(3)	0.100(0.075)	[1,11]
NGC 2539	8.80	0.06	10.60	0.018	−0.04	100(20)	1(1)	0.010(0.050)	[1,19,20]
NGC 2477	8.85	0.28	10.50	0.018	−0.05	330(190)	15(28)	0.045(0.147)	[1,15]
IC 4756	8.90	0.23	7.60	0.022	0.04	80(55)	6(1)	0.075(0.018)	[1,11]
NGC 5823	8.90	0.50	10.50	0.016	−0.10	35(35)	1(1)	0.029(0.029)	[1,4,16]
Collinder 223	8.00	0.25	13.00	0.02?	...	25(25)	2(2)	0.080(0.080)	[1,21]
NGC 5617	8.15	0.54	11.53	0.02?	...	65(70)	0(9)	0.000(0.129)	[1,3]
NGC 5460	8.30	0.144	9.49	0.02?	...	20(20)	0(1)	0.000(0.050)	[1,12]
Melotte 105	8.40	0.52	11.80	0.02?	...	80(25)	4(1)	0.050(0.040)	[1,7]
NGC 2383	8.60	0.22	13.30	0.02?	...	5(5)	1(1)	0.200(0.200)	[1,13]
NGC 2818	8.70	0.22	12.90	0.02?	...	45(45)	2(5)	0.044(0.111)	[1,18]

Notes: Columns (1)–(6) are cluster name, age, color excess, distance modulus, metallicity (Z) and [Fe/H]. Columns (7)–(9) are N_2 (number of stars within 2 mag below the main-sequence turn-off stars), $N_{\rm BS}$ in the sample clusters from observations and the frequency $f = N_{\rm BS}/N_2$ (the data in brackets are from Xin07). The last column is the references for the data. [1] AL07; [2] Terndrup et al. (2002); [3] Ahumada (2005); [4] Kharchenko et al. (2005); [5] Loktin & Matkin (1994); [6] Dias et al. (2002); [7] Sagar et al. (2001); [8] van Leeuwen (1999); [9] Burke et al. (2004); [10] Subramaniam (2003); [11] Hebb et al. (2004); [12] Barrado & Byrne (1995); [13] Subramaniam & Sagar (1999); [14] Claria et al. (1994); [15] Eigenbrod et al. (2004); [16] Janes (1981); [17] Clariá et al. (2003); [18] Surendiranath et al. (1990); [19] Marshall et al. (2005); [20] Lapasset et al. (2000); [21] Tadross (2004).

AL07. A cluster star is assumed to be a BS candidate if it is located in the shaded area in the CMD of the cluster as shown in Figure 3. In addition to the shaded area, it is also physically reasonable to consider stars that have a blue offset of ZAMS and stars that are brighter than and somewhat redder than the TO of the cluster. We adopt the selection criterion similar to AL07 in our work. Simulations for the BS populations in six clusters, namely IC 2488, IC 2714, NGC 1245, NGC 6633, NGC 2477 and IC 4756, are presented in Figure 4. In fact, realistic simulations of the sample clusters may have large dispersion in the results due to the relatively low number of massive member stars in young clusters. Therefore, the simulations are made with 10^6 artificial primordial binaries so that the number of theoretical BSs in Figure 4 is of course much larger than that observed. This is only considered as an indication of the possible locations of the BS models. The results are shown in Figure 4 in which a pair of CMDs are given for each of the selected clusters. The upper one is for the conservative case while the lower one is for the non-conservative case. In each of the plots, the observed BSs are shown in open squares. The solid line is the corresponding isochrone that best fits the cluster parameters (also indicated on the figure). Dots are simulated BS models. Points in black, blue and red are BSs formed via Case A, B and mergers respectively.

The distributions of BSs on CMDs are different between the conservative and the non-conservative cases. We have adopted a constant β in LDZ10 to estimate BSs formed via a non-conservative case in M67. The result shows that in M67 a high value of β can reproduce the lumi-

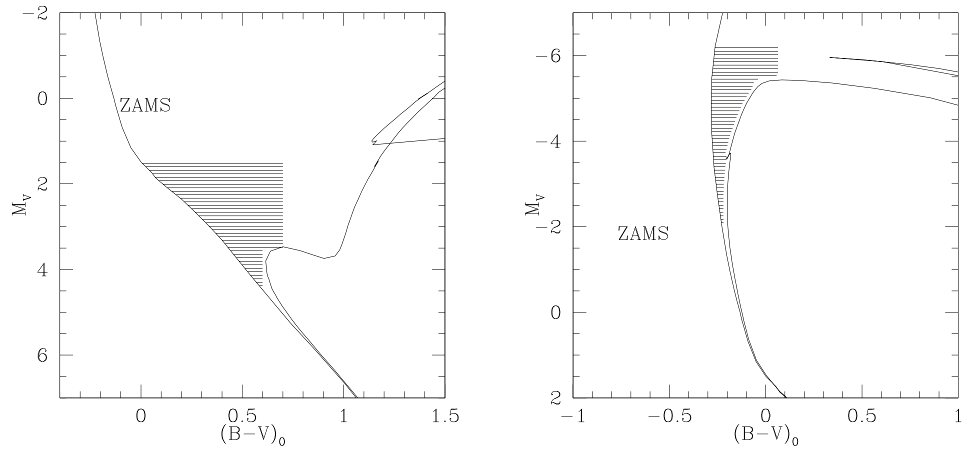

Fig. 3 CMDs for an old open cluster and a young open cluster: the isochrones correspond to log (age) = 9.8 for the left and log (age) = 7.5 for the right. The blue straggler areas are shaded.

nous BSs better, while a lower value can match the number of BSs with low luminosity better. Both results show that the number of BSs could be significantly increased by taking into account Case B.

In this work, we also adopt $\beta = 0.5$ as in many previous works for Case B mass transfer to simulate non-conservative cases. This means that 50% of the mass transferred during RLOF will be lost. After we consider this assumption, the most prominent change on the CMD is that the luminosity of Case B models decreases, but the number of BS candidates increases. We can see from Figure 4 that in some of the clusters, a lower mass transfer efficiency is needed to fit the observed BSs, such as NGC 6633 which has four BS candidates (HD 170563, HD 170472, HD 169959 and HD 170054). By taking $\beta = 0.5$, the faintest BS (HD 170054) can almost be covered by our models. HD 170563 might be a BS formed by Case A mass transfer according to its location on the CMD. IC 2488 is a young cluster with log(age)=8.25, in which the observed BS can be easily confirmed by the conservative models. The two BSs toward the blue side are most likely formed via Case B or mergers. In IC 2714, we noticed that either the conservative or the non-conservative models can fit the observational BSs because the two stars are both located very close to the ZAMS. We also noticed that not all our models can explain the observed BSs in all these clusters as an entity. All the observed BSs in NGC 1245 are too faint compared to the cluster's age. Although the BSs formed via AML can contribute to low luminosity BSs, the cluster is so young that the role of AML cannot be so remarkable. There is a clear shift in the V band in NGC 2477. We cannot match the observations unless there is a shift of ~ 1.5 mag in the distance modulus (DM) or we adopt an older cluster age. In fact, the cluster age is different from 1.0 Gyr taken from Xin et al. (2007), hereafter Xin07. The parameters of this cluster need to be confirmed. In IC 4756, all the observed BSs show an extreme color toward the blue side and a wide distribution in magnitude. The color exceeds 0.2 toward the blue side from the color limit of our simulation. Enhancement of surface helium abundance of BSs may lead to a bluer color (Chen & Han 2004, 2008), but 0.2 is too big for any possible mechanisms. The reason for He enrichment might be that they were formed via mass transfer between an AGB and an MS star. However, an AGB star can only provide He rich material if it is older than 2.24 Gyr for Population I (Chen & Han 2009); it is difficult to imagine that all of the BSs in IC 4756 are formed in that single way. The observed BSs of IC 4756 cannot be explained by mass transfer or merger in our work, if the observed colors are correct.

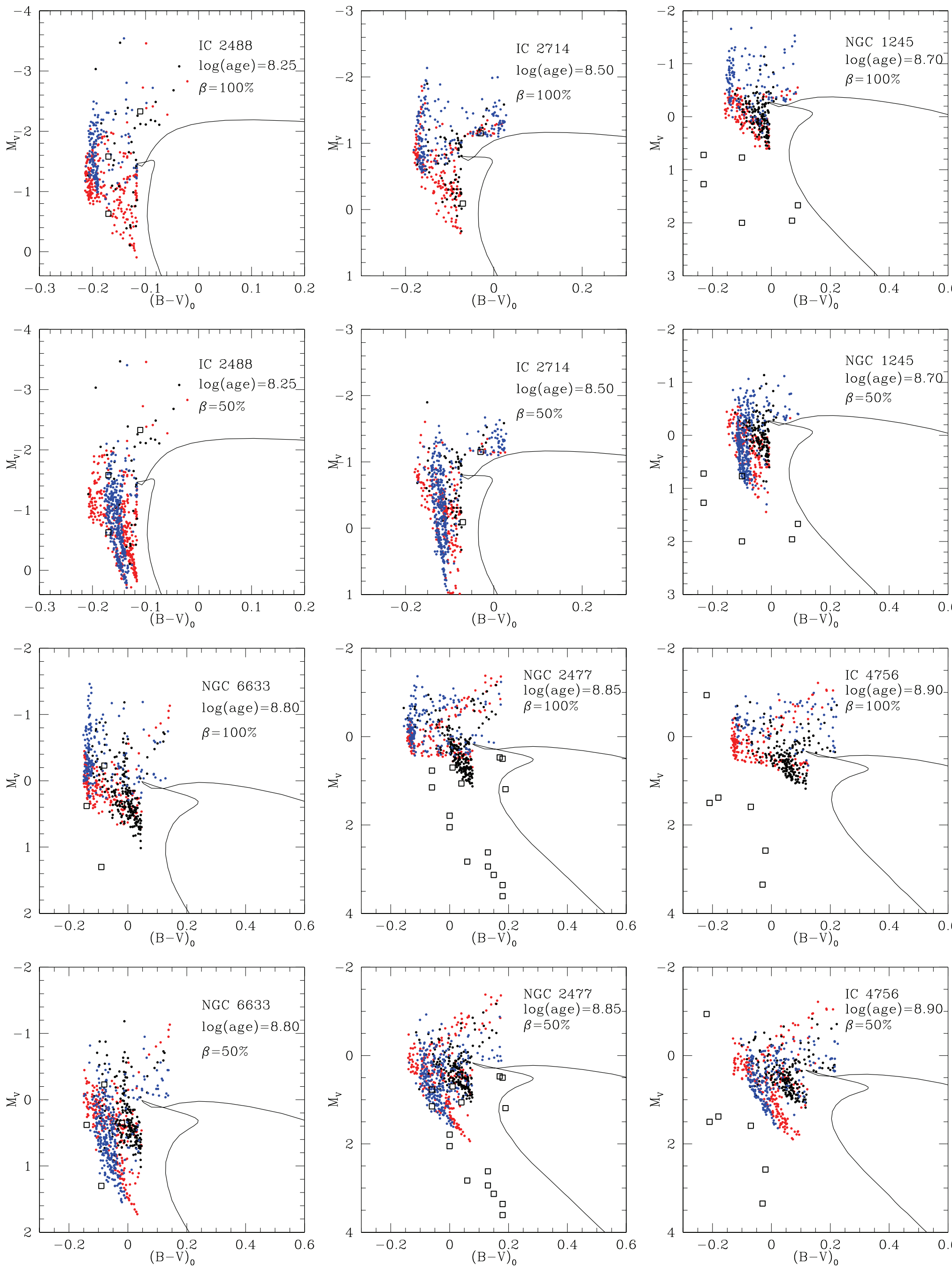

Fig. 4 CMDs of our simulated star clusters with $\beta = 1$ in the upper panel and $\beta = 0.5$ in the lower panel for each pair. The samples are IC 2488, IC 2714, NGC 1245, NGC 6633, NGC 2477 and IC 4756 in order. Open squares are the observed BSs from sample clusters in AL07. Points in black, blue and red are BSs formed via Case A, B and mergers respectively (color online).

Two distinct sequences of BS populations are found in M30 which can be explained by direct collisions and evolutions of close binaries respectively. We notice two distinct sequences in our samples similar to those in M30, such as NGC 1254, NGC 6633, IC 2477 and IC 4756 when $\beta = 1$ (Fig. 4), however, we have different explanations. These two sequences are mainly from different evolutionary channels. Case B and merger models dominate the blue sequence, in which Case B examples mainly populate the luminous part of the sequence. The Case A models are only visible in a region close to the ZAMS in relatively older clusters. When we take $\beta = 0.5$, the BSs formed via Case B have a luminosity about 1.0 mag lower and are degenerate with the mergers, or they move closer to the ZAMS (IC 2488), so that the sequences cannot be observed.

In some young clusters such as IC 2488 and IC 2714, we notice only one sequence located to the blue side of the ZAMS which is formed by mergers and Case B examples; the other sequence is formed via a situation where Case A is prominent in older clusters which are no longer visible. We infer from the results that Case A can hardly contribute to the observed BSs in young clusters as we concluded in our previous work (Lu & Deng 2008). It can also be explained by our models in three aspects.

(1) With a flat distribution of initial orbital separations in $\log(\alpha)$, BS production due to Case B models is dominant in massive binaries.
(2) The durations of RLOF in Case B models become shorter for higher initial donor masses. The companions in massive binaries tend to spend less time on RLOF and evolve faster toward the blue side, possessing most of the system masses. Then they evolve for the rest of their lives as BSs.
(3) BSs formed via Case A which are still experiencing mass transfer tend to form a redder BS sequence ~ 0.75 mag above the ZAMS in the BS region. Those BSs can sometimes become degenerate with the MS stars that are sitting on nearly vertical ZAMS in young clusters.

4.1 The Specific Frequency

In Table 2, apart from the basic physical parameters, statistics of BS populations in the sample clusters are also given. Columns 7, 8 and 9 are respectively N_2, $N_{\rm BS}$ and the corresponding specific frequencies of BS defined as f=$N_{\rm BS}/N_2$. The value of N_2 and $N_{\rm BS}$ are significantly different among various authors. For NGC 2516 and NGC 5617, the values of $N_{\rm BS}$ are quite different between AL07 and Xin07. For NGC 2539, the value of $N_{\rm BS}$ agrees well in AL07 and Xin07. However, the value of N_2 of AL07 is five times that of Xin07. There are also some uncertainties in age and distance modulus from the observations. For instance, the age of NGC 2477 is 8.85 in AL07 and 9.00 in Xin07.

It is believed that there might be a relationship between the number of BSs and the total number of stars usually represented by stars within 2 mag below the TO. Xin07 gave the $N_{\rm BS}$ distributions with respect to three different parameters: log (age), Z and N_2 based on observations. The only correlation found is that between $N_{\rm BS}$ and N_2. Chen & Han (2009) discussed this issue and estimated the frequency of $N_{\rm BS}$/N_2 with theoretical models. The result showed that the frequency decreased with increasing log (age) between 8.0 and 10.0. The AML becomes important only when $\log$ (age)$>$9.0. The contribution of BSs formed via coalescence to the specific frequency is negligible (Chen & Han 2009). We also estimated the relationship of $N_{\rm BS}$/N_2 with $\log$ (age) from 7.85 to 8.90 using our models. The results are presented in Figure 5 with solid dots. There seems to be a correlation between age and f. Our results agree with Chen & Han (2009) but our f values are a little higher. The reason could be that we take mergers due to low mass ratio binaries into account and use a different definition of N_2. We use the same method as Hurley et al. (2002) to treat a binary as a single star in our work while in Chen & Han (2009), a binary is assumed to be two single stars and the evolution of the primary has not been continued after RLOF. f values from the non-conservative case are also plotted in Figure 5 with open circles. We also notice that the specific

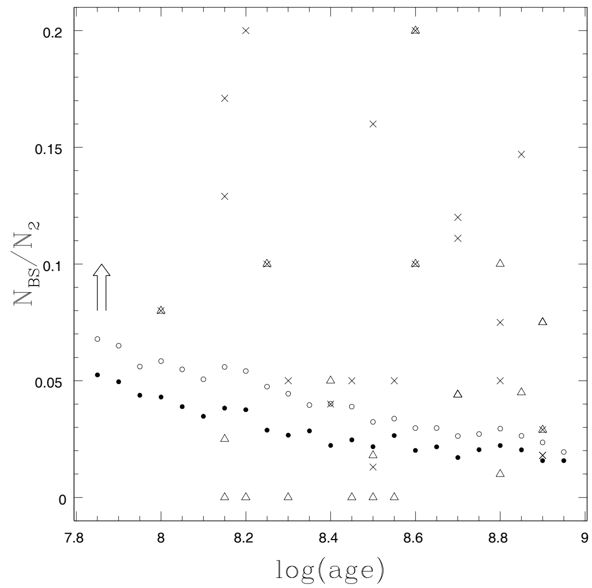

Fig. 5 Frequency f=$N_{\rm BS}/N_2$ versus cluster age. Dots ($\beta = 1.0$) and open circles ($\beta = 0.5$) are the results of our simulation. Open triangles and crosses are f from AL07 and Xin07 respectively.

frequency is higher than the conservative case because the number of BSs (usually fainter) will increase for lower β, as discussed above. The observed frequencies in terms of $N_{\rm BS}/N_2$ for sample clusters from AL07 (open triangles) and Xin07 (crosses) are also shown in the figure. We can see from the figure that only a few clusters fall into the simulation predictions. Obviously, the dispersion of observed specific frequencies of BSs is too large as discussed at the beginning of this section, primarily due to stochastic effects of the low number of member stars in these clusters. Dynamic interactions between member stars within the cluster and with the environments also play an important role in the scatter of the observed f. Our simulation considers only stellar evolution, therefore it cannot fully interpret the observations. More realistic simulations for open clusters should take into account all these effects, which is out of the scope of the current work.

There are also uncertainties in the initial parameters of our simulations (i.e. IMF, distribution of q and orbital separations). The parameters may be different from reality. For instance, the IMF is still an open problem and it is uncertain whether it is universal in any stellar systems or not. The binary frequency in star clusters is also a very important issue for BS formation. Moreover, dynamical processes in star clusters may also have an influence, though limited in young clusters. The observational $N_{\rm BS}/N_2$ needs to be normalized to make a better comparison.

After all, there are some difficulties in comparing $N_{\rm BS}/N_2$ from simulations and observations. There are very few BSs in young clusters due to the low number of member stars (few N_2 stars). The $N_{\rm BS} - N_2$ correlation is still inchoative for currently available data. More observations are needed to study the relations between $N_{\rm BS}$ and N_2.

5 SUMMARY AND CONCLUSIONS

We investigated BSs generated from a mass transfer scenario and simulated BS populations in young clusters in this work. BSs can be produced via various mechanisms (Piotto et al. 2004). Observed

BSs in clusters cannot be accounted for by a single mechanism. In general, BSs could be formed by mass transfer in primordial binaries, which dominates BS formation in a sparse environment (Mathys 1991), or through direct collisions, which are considered to be crucial in a dense stellar environment (Fregeau et al. 2004).

The dynamical processes are not considered in this work because we discuss those BSs which only formed in a mass transfer scenario. We choose young clusters as working samples in order to avoid the complicated effects of dynamical evolution. In reality, dynamic processes destroy primordial binaries while creating new ones through capture and exchange processes (Hurley et al. 2005). Mass segregation can also enhance BS formation in cluster cores. Magnetic activities, as discussed in Section 2, can also affect the number of BSs through AML (Li et al. 2004Li et al. 2004b Li et al. 2004a; Demircan et al. 2006; Politano & Weiler 2006; Stepien 2006), however it is only important in clusters older than 10^9 yr (Chen & Han 2009).

We apply the same method as LDZ10 to calculate a grid of close binary evolution models undergoing both Case A and B RLOF in a wider donor mass range. The formation and lifetime of BSs are thoroughly analyzed using the models. Our results show that Case B produces bluer, brighter and longer lived BSs than Case A, therefore Case B is more effective in producing BSs than Case A, especially in young clusters.

Based on the grid of all our models at a given age, Monte-Carlo simulations were carried out for a number of clusters from AL07. The results show that BSs formed via different scenarios populate different areas on CMD. Mass transfer efficiency is considered in this work. A constant mass transfer efficiency of 0.5 is adopted for the comparison between conservative and non-conservative cases. The results show a high value of β (conservative case) can reproduce luminous BSs through the Case B scenario while a lower value case ($\beta = 0.5$) can increase the number of BSs with low luminosity. Case A is less important in young clusters as predicted in Lu & Deng (2008). Case B and merger models become more important for clusters with younger ages. The specific frequency of $f = N_{\rm BS}/N_2$ is studied. The result is less conclusive in the current scheme.

Two separated sequences can be noticed in CMD in the clusters between $\log(age) > 8.7$ up to nearly 1.0 Gyr (Fig. 5). Case B and merger models dominate the blue sequence, in which Case B examples mainly populate the luminous part of the sequence. The Case A models are only visible in a region close to the ZAMS in relatively older clusters. This may provide a new clue to the two sequences of BSs observed in globular clusters (Ferraro et al. 2009).

The grid of detailed binary evolution models in this work covers a large parameter space, which can account for all possible binary mass transfer processes. Therefore, this grid of models can serve future studies on star clusters. By implementing dynamics, more realistic simulations of star clusters, including under-populated open clusters, are possible. This will be part of our future work.

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