Contribution of Primordial Binary Evolution to the Two Blue-straggler Sequences in Globular Cluster M30

Dengkai Jiang1,2,3, Xuefei Chen1,2,3, Lifang Li1,2,3, and Zhanwen Han1,2,3

1 Yunnan Observatories, Chinese Academy of Sciences, 396 Yangfangwang, Guandu District, Kunming, 650216, P.R. China; dengkai@ynao.ac.cn, zhanwenhan@ynao.ac.cn
2 Center for Astronomical Mega-Science, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, 100012, China
3 Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming, 650011, China

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Abstract

Two blue-straggler sequences discovered in globular cluster M30 provide a strong constraint on the formation mechanisms of blue stragglers. We study the formation of blue-straggler binaries through binary evolution, and find that binary evolution can contribute to the blue stragglers in both of the sequences. Whether a blue-straggler is located in the blue sequence or red sequence depends on the contribution of the mass donor to the total luminosity of the binary, which is generally observed as a single star in globular clusters. The blue stragglers in the blue sequence have a cool white dwarf companion, while the majority (∼60%) of the objects in the red sequence are binaries that are still experiencing mass transfer. However, there are also some objects for which the donors have just finished the mass transfer (the stripped-core stars, ∼10%) or the blue stragglers (the accretors) have evolved away from the blue sequence (∼30%). Meanwhile, W UMa contact binaries found in both sequences may be explained by various mass ratios, that is, W UMa contact binaries in the red sequence have two components with comparable masses (e.g., mass ratio $q \sim 0.3–1.0$), while those in the blue sequence have low mass ratios (e.g., $q < 0.3$). However, the fraction of the blue sequence in M30 cannot be reproduced by binary population synthesis if we assumed the initial parameters of a binary sample to be the same as those of the field. This possibly indicates that dynamical effects on binary systems are very important in globular clusters.

Key words: binaries: general – blue stragglers – globular clusters: individual (M30, NGC 7099) – stars: evolution

1. Introduction

Blue stragglers are a class of anomalous stars that are brighter and bluer than the main-sequence (MS) turnoff stars in the color–magnitude diagram of globular clusters. They are very common objects in almost all Galactic globular clusters (Piotto et al. 2004), and can be used to probe the dynamical evolution of clusters (Ferraro et al. 2012). Their locations in the color–magnitude diagram suggest that they may be MS stars more massive than typical MS turnoff stars (Ferraro et al. 2006), and they should have evolved away from the main sequence.

At present, there are two popular mechanisms to explain the formation of blue stragglers, binary evolution (McCrea 1964) and direct stellar collision (Hills & Day 1976), and in the past 10 years, a series of works have been performed to study these mechanisms (e.g., Sills & Bailyn 1999; Sills et al. 2000; Tian et al. 2006; Xin et al. 2007; Chen & Han 2008a, 2008b, 2009; Lu et al. 2010; Leigh et al. 2013). It is generally believed that binary evolution plays an important role in open clusters and in the field, while direct stellar collisions are likely important in dense environments such as globular clusters or the cores of open clusters (Hills & Day 1976; Sills et al. 2002; Glebbeek et al. 2008; Mathieu & Geller 2009; Geller & Mathieu 2011). However, observations show that the two mechanisms may be important in the same clusters (Ferraro et al. 1993, 1995, 1997, 2004).

An important and perhaps critical clue to the origin of blue stragglers is the two blue-straggler sequences observed in the color–magnitude diagram of globular cluster M30 (Ferraro et al. 2009). Similar features are also found in NGC 362 (Dalessandro et al. 2013) and NGC 1261 (Simunovic et al. 2014). The occurrence of two sequences can be explained by the coexistence of blue stragglers formed through two different formation mechanisms enhanced by core collapse 1–2 Gyr ago (Ferraro et al. 2009). Each of the two sequences may correspond to a distinct formation mechanism (Ferraro et al. 2009), because the blue sequence is outside the “low-luminosity boundary” defined by the binaries with ongoing mass transfer (Tian et al. 2006; Xin et al. 2015) and the red one is too red to be reproduced by collisional models (Sills & Lattanzio 2009). However, NGC 1261, one of three globular clusters with two blue-straggler sequences, does not show the classical signatures of core-collapse (Simunovic et al. 2014).

It should be noted that three W UMa contact binaries have been detected in both sequences of blue stragglers in M30 (Pietrukowicz & Kaluzny 2004; Ferraro et al. 2009). W UMa contact binaries are very common among blue stragglers in globular clusters (Rucinski 2000), which are thought to come mainly from binary evolution (Vilhu 1982; Jiang et al. 2014a). Hence, the formation of both sequences may be related to the binary evolution. Meanwhile, Lu et al. (2010) found that some blue stragglers produced by Case B binary evolution are below the low-luminosity boundary given by Tian et al. (2006), Chen & Han (2008a) show that binary mergers can produce single blue stragglers very close to or even below the zero-age main sequence (ZAMS), i.e., in the blue sequence. In addition, Stepien & Kiraga (2015) found that binary mergers can form a blue sequence of blue stragglers, while binary blue stragglers can lead to a red sequence. Therefore, more studies of the formation of blue stragglers by binary evolution should be done to check whether binary evolution can provide a contribution to the formation of the blue-straggler blue sequence in globular cluster M30.
two kinds of blue-straggler binaries. (1) Case A binary evolution may produce blue straggler binaries that are experiencing mass transfer. (2) Case B binary evolution may produce blue-straggler binaries that have finished mass transfer and have a blue straggler orbiting a white dwarf (the BS–WD binaries).

2. The Possibility of Binary Evolution Contributing to the Blue-sequence Blue Stragglers

Before detailed binary evolution calculations are performed, we will simply discuss the possibility of binary evolution contributing to the blue-sequence blue stragglers. At first, if not considering contact binaries, binary evolution can produce two kinds of blue-straggler binaries (as shown in Figure 1); those that are still experiencing mass transfer (e.g., V228 in 47 Tuc, Kaluzny et al. 2007) and those that have finished mass transfer (e.g., WOCS 4348, 4540, and 5379 in NGC 188, Gosnell et al. 2014). The blue-straggler binaries in the mass transfer phase have a “low-luminosity boundary” (about 0.75 mag brighter than the ZAMS) given by Tian et al. (2006), and can match the observed red-sequence blue stragglers in globular cluster M30 (Ferraro et al. 2009; Xin et al. 2015). However, for the blue-straggler binaries that have finished mass transfer, including a blue-straggler and a white dwarf (the BS–WD binaries), their locations in the color–magnitude diagram of M30 depend on the contribution of white dwarfs to the combined magnitudes of these binaries.

We can estimate the location of a BS–WD binary in the color–magnitude diagram as follows. We take the binaries with a 0.8 $M_\odot$ primary (metallicity Z = 0.0003) as examples, then the secondary masses are taken to be 0.75, 0.7, 0.65, ..., 0.3$M_\odot$. These binaries are assumed to experience Case B mass transfer at about 12 Gyr. The primaries will transfer their envelopes (about 0.55 $M_\odot$ in a conservative case of mass transfer) to the secondaries, leaving a helium WD star (about 0.25$M_\odot$). The secondaries that gain mass will rejuvenate and evolve up along the main sequence to higher luminosity and effective temperature (Tout et al. 1997; Hurley et al. 2002). When mass transfer finishes (assuming at about 12.5 Gyr), the secondaries become blue stragglers with masses of 1.3, 1.25, 1.2, ..., 0.85 $M_\odot$ as rejuvenated stars. We approximate this rejuvenation\(^4\) as described by Tout et al. (1997) and Hurley et al. (2002). After the rejuvenation, these blue stragglers continue to evolve as single stars.

At the time of the end of mass transfer, the primaries are the stripped giant stars, which are brighter and redder than the turnoff. So we simply assume that they have the same magnitude and color as a single star with 0.8 $M_\odot$ at the red giant branch (e.g., $V \sim 2.5$ and $V - I \sim 0.6$). By combining their companions (the rejuvenated stars), the combined magnitude of these BS–WD binaries can be calculated using a formula given by Xin et al. (2015). For example, the $V$-band magnitude of the binary system

$$V = V_1 - 2.5 \log (1 + 10^{(V_2 - V_1)/2.5}),$$

(1)

where $V_1$ and $V_2$ are the $V$-band magnitudes of two components, respectively. After mass transfer terminates, these primaries evolve quickly to a helium white dwarf and cool down. According to the equation of luminosity evolution of white dwarfs given by Hurley et al. (2000),

$$L_{WD} = \frac{635M_Z^{0.4}}{[(A(t + 0.1))]^{2.3}}$$

(2)

(where $M$, $Z$, $A$, and $t$ are the mass, metallicity, effective baryon number, and age of white dwarfs, respectively), these white dwarfs would have much lower luminosities than their blue-straggler companions when they cool to the age of M30 (13 Gyr) from the end of mass transfer (12.5 Gyr). Here, we roughly assume that the $V$-band magnitude of the white dwarfs increases with their age (e.g., $V_{WD} = V_{BS} + 3$ at 13.0 Gyr, $V_{WD} = V_{BS} + 4$ at 14.0 Gyr), while these white dwarfs have a color $V - I = -0.2$.

In Figure 2(a), we show the locations of these BS–WD binaries in the color–magnitude diagram at the time of the end of mass transfer (12.5 Gyr), at the age of M30 (13.0 Gyr), and at their subsequent evolution (e.g., 14.0 Gyr). When the mass transfer terminates, these binaries are above the “low-luminosity boundary,” which is 0.75 mag brighter than the ZAMS as suggested by Tian et al. (2006). They then move to the region below the “low-luminosity boundary” when the primaries become a helium WD and cool to the age of M30. They mainly appear in the location between the ZAMS and the boundary at 13.0 Gyr and 14.0 Gyr, which contains the blue sequence defined by Ferraro et al. (2009). Therefore, it is possible that the BS–WD binaries may contribute to the blue sequence in M30.

It should be noted that at the time of the end of mass transfer, these binaries have very different locations from the blue-straggler components as shown in Figure 2(a), because the primaries (stripped giant stars) are brighter than the blue-straggler components dominating the positions of these binaries. As the white dwarfs cool, they are closer to the BS–WD binaries, and almost overlap with the BS–WD binaries at 14.0 Gyr. The faint blue-straggler components are close to the

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\(^{4}\) According to the description of Tout et al. (1997), the rejuvenation of main-sequence stars with no convective core (0.3 ~ 1.3$M_\odot$) can be approximated by taking the remaining fraction of main-sequence life directly proportional to the remaining fraction of unburnt hydrogen at the center, and adjusting the effective age $t$ of the stars, $t' = t \times (t_{MS}/700).$
ZAMS because their progenitors are less evolved, low-mass stars. Considering the effect of non-conservative mass transfer (e.g., 50% of the transferred mass is assumed to be lost during mass transfer), the BS–WD binaries are still below the “low-luminosity boundary.” However, there are no bright and blue BS–WD binaries because of the decrease of accreted mass of the secondaries. Moreover, in Figure 2(b), we compare these BS–WD binaries with the collision isochrones corresponding to ages of 1 and 2 Gyr given by Sills & Lattanzio (2009), which agree with the observed blue sequence as shown by Ferraro et al. (2009). The collisional isochrones have been transferred into the absolute plane using a distance modulus of \((m - M)_V = 15.04 \text{ mag}\) and a reddening of \(E(V - I) = 0.112 \text{ mag}\) (see the text).

3. Binary Evolution Calculations

We have carried out a detailed study of the formation of blue stragglers from binary evolution using Eggleton’s stellar evolution code. This code is a variant of the code ev, described in its initial version, by Eggleton (1971, 1972) and Eggleton et al. (1973a), and updated over the last four decades (Eggleton 1973b; Han et al. 1994; Pols et al. 1995; Nelson & Eggleton 2001; Eggleton & Kisseleva-Eggleton 2002; Yakut & Eggleton 2005; Eggleton & Kisseleva-Eggleton 2006). The current version of ev (private communication 2003) is obtainable upon request from Peter Eggleton (via peter. eggleton@yahoo.com), along with data files and a user manual. We calculate the evolution of binaries with metallicity \(Z = 0.0003\), which are close to the metallicity \((\text{Fe/H}) = -1.9\) of M30 (Ferraro et al. 2009). We construct a grid of conservative binary evolution models from ZAMS to the age of M30 (13 Gyr), with the following ranges of initial primary mass \(M_{10}\), initial mass ratio \(q_0 = m_{20}/M_{10}\), and initial orbital period \(P_0\):

\[
\log M_{10} = -0.110, -0.105, -0.100, \ldots, -0.02, \quad (3)
\]

\[
\log(1/q_0) = 0.025, 0.050, 0.075, \ldots, 0.600, \quad (4)
\]

\[
\log(P_0/P_{\text{ZAMS}}) = 0.025, 0.050, 0.075, \ldots, 1.000, \quad (5)
\]

where \(P_{\text{ZAMS}}\) is the period at which the primary would just fill its Roche lobe on the ZAMS (Nelson & Eggleton 2001). We assume that the binary orbit is circular because it will circularize quickly during the mass transfer.\(^5\) In Eggleton’s Stellar evolution code, the magnitude of each component is given from the luminosity and effective temperature based on the table given by Flower (1996). Then, we calculate the combined magnitude of blue-straggler binaries using Equation (1).

Four representative examples of our binary evolution calculations are shown in Figure 3. The first example is a blue-straggler binary that is experiencing mass transfer, and appears in the red sequence at the age of M30. The other three examples are the BS–WD binaries that can evolve into the blue sequence. However, at the age of M30, the second example appears in the blue sequence, while the third and fourth examples appear in the red sequence.

Figures 5(a) and (b) show the evolutionary track of the first example, including the combined evolutionary tracks of the binary system and both components. Mass transfer begins at 10.44 Gyr, and this system evolves into the region of a blue-straggler along a line parallel to the “low-luminosity boundary.” This binary is in the observed red sequence region at 13 Gyr, while it is still in the mass transfer stage. At this time, the donor star is in the red giant branch at 13 Gyr, and its luminosity is high enough to significantly change the position of this binary relative to the accretor star \((\Delta V = -0.2; \Delta (V - I) = -0.14)\) in the color–magnitude diagram. Finally, this binary leaves the blue-straggler region at about 13.63 Gyr.

For the second example in Figures 5(c) and (d), mass transfer between two stars begins and terminates at 9.91 and 10.86 Gyr, respectively, then this BS–WD binary evolves across the “low-luminosity boundary.” At the age of globular cluster M30 (13 Gyr), this binary is in the region between the ZAMS and the “low-luminosity boundary,” where the observed blue sequence in M30 lies. It should be noted that after the end of mass transfer, the location of this BS–WD binary depends on two timescales: (1) the timescale for the white dwarf that cools to almost no contribution to the V-band magnitude (e.g., the location of the BS–WD binary with the largest V-band magnitude at 11.08 Gyr), which is about 0.22 Gyr; and (2) the timescale for the remaining main-sequence lifetime of the blue-straggler (about 2 Gyr). The

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\(^5\) The originally eccentric orbits would be circularized quickly during mass transfer (Hurley et al. 2002), and only a few evolved binaries have eccentric orbits (e.g., de Mink et al. 2007). However, the parameter space for the formation of blue stragglers at 13 Gyr may be smaller if the mass transfer does not always lead to circular orbits, as suggested by Sepinsky et al. (2007, 2009, 2010). This is because mass transfer in the eccentric binaries may be episodic (only at periastron), which results in the less massive, more evolved accretor stars than those seen in the circular binaries.
cooling timescale is much shorter than the remaining MS lifetime of the blue-straggler. Therefore, this BS–WD binary experiencing mass transfer; (2) blue sequence: a BS–WD binary where the white dwarf is cooled down and has little contribution; (3) red sequence: BS–WD binary where the white dwarf is bright and hot; (4) red sequence: BS–WD binary where the blue straggler has evolved away from the main sequence. The red solid lines show the combined evolutionary tracks of the binary systems in the left panels, while the blue solid lines are for the primaries and the blue dashed lines are for the secondaries in the right panels. The initial binary parameters are also given in the left panels. The numbers along the tracks give the ages (in Gyr) of selected phases (black open circles): the beginning of mass transfer, the age of M30, and the final model for the first example; the beginning of mass transfer, the end of mass transfer, the largest V-band magnitude, and the age of M30 for other examples. The dotted, dashed, and dashed–dotted lines correspond to the single-star isochrone of 13 Gyr, the ZAMS, and the “low-luminosity boundary,” respectively. In panels (a) and (c), the time intervals between two pluses are 0.4 Gyr, and those between two crosses are 0.04 Gyr.

Figure 3. Four examples of binary evolution for the formation of blue stragglers in two sequences at the age of M30 (13 Gyr): (1) red sequence: the blue-straggler binary experiencing mass transfer; (2) blue sequence: a BS–WD binary where the white dwarf is cooled down and has little contribution; (3) red sequence: BS–WD binary where the white dwarf is bright and hot; (4) red sequence: BS–WD binary where the blue straggler has evolved away from the main sequence. The red solid lines show the combined evolutionary tracks of the binary systems in the left panels, while the blue solid lines are for the primaries and the blue dashed lines are for the secondaries in the right panels. The initial binary parameters are also given in the left panels. The numbers along the tracks give the ages (in Gyr) of selected phases (black open circles): the beginning of mass transfer, the age of M30, and the final model for the first example; the beginning of mass transfer, the end of mass transfer, the largest V-band magnitude, and the age of M30 for other examples. The dotted, dashed, and dashed–dotted lines correspond to the single-star isochrone of 13 Gyr, the ZAMS, and the “low-luminosity boundary,” respectively. In panels (a) and (c), the time intervals between two pluses are 0.4 Gyr, and those between two crosses are 0.04 Gyr.

As products of binary evolution, the blue-straggler binaries in the two sequences may have different initial binary parameters. We show their initial binary parameters in the initial orbital period-secondary mass planes for different initial primary masses (Figure 4). They are roughly classified based on whether they are above or below the “low-luminosity boundary” (0.75 mag brighter than the ZAMS). The progenitors of the blue sequence are constrained to host $0.80–0.93 M_\odot$ primaries and $0.23–0.76 M_\odot$ secondaries in orbits with initial orbital periods of 0.4–2.3 day. The range of initial primary mass for the red sequence is slightly larger than that for the blue sequence. However, the blue stragglers in the red sequence have a shorter initial orbital period and a more massive initial secondary than those in the blue sequence with the same initial primary masses. In general, the blue sequence mainly comes from case B binary evolution, while the red sequence mainly comes from case A binary evolution.
4. Binary Population Synthesis

In order to estimate the distribution of blue-straggler binaries, we performed a series of Monte Carlo simulations (see Table 1) based on our grid of conservative binary evolutionary models described above. The following input is adopted for the simulation (Han et al. 1995). (1) The initial mass function (IMF) of Miller & Scalo (1979, MS79) is adopted. An alternative IMF of Scalo (1986, S86) is also considered. (2) We adopt three initial mass-ratio distributions: a constant mass-ratio distribution, a rising mass-ratio distribution, and one where the component masses are uncorrelated. (3) The distribution of separations is taken to be constant in log a for wide binaries, where a is the orbital separation. We also take a different period distribution from Duquennoy & Mayor (1991, DM91). (4) A circular orbit is assumed for all binaries.

Figure 5 shows the result of simulation set 1 at 13 Gyr in the color–magnitude diagram. It is striking that this simulation agrees quite well with the distribution of the observed blue stragglers in M30. There is a blue-straggler sequence, similar to the observed blue sequence, that is between the ZAMS and the “low-luminosity boundary” and about half a magnitude brighter than the ZAMS. Meanwhile, the blue stragglers above

| Set | IMF | $n(q_0)$ | $a$ |
|-----|-----|---------|-----|
| 1   | MS79| Constant| Constant |
| 2   | MS79| Rising  | Constant |
| 3   | MS79| Uncorrelated | Constant |
| 4   | S86 | Constant| Constant |
| 5   | MS79| Constant| DM91  |

Note. IMF—initial mass function; $n(q_0)$—initial mass-ratio distribution; $a$—the distribution of orbital separation.
the “low-luminosity boundary” cover a wider, sparser area, which agrees with the distribution of the observed red sequence. The blue-sequence binaries have a blue-straggler orbiting a white dwarf, while the red-sequence binaries include binaries that are experiencing mass transfer (∼60%), or just terminating mass transfer (∼10%), and the binaries that the blue stragglers have evolved away from the blue sequence (∼30%). The results of other Monte Carlo simulations (sets 2–5) are plotted in Figure 6, and these simulations give results similar to those of simulation set 1. These four simulations also show the presence of two blue-straggler sequences that are in agreement with the observed distribution of blue stragglers in M30.

To estimate the total number of blue stragglers and the fraction of the blue sequence in M30 from binary population synthesis, we assume an initial binary fraction \( f_0 \) of M30, e.g., 25%, which is half of the binary fraction in the solar neighborhood (50%, Halbwachs et al. 2003). As alternatives we also consider a binary fraction of 15%. These fractions are assumed to be higher than the binary fraction of M30 at present day (about 7%, Milone et al. 2012) because the binary fraction decreases with time due to dynamical interactions and binary evolution (Ivanova et al. 2005). In addition, the initial mass of M30 is simply assumed to be twice as massive as the current mass of M30 (\( \log(M/M_\odot) = 5.3 \), Sandquist et al. 1999) as the globular clusters may have lost a significant fraction of total mass due to relaxation, stellar evolution, and the tidal field of the Galaxy (Vesperini & Heggie 1997). Because the binaries are more difficult to lose from the globular clusters than single stars, the binary fraction in the lost stars is assumed to be half of the initial binary fraction.

The results are summarized in Table 2 for the total number of blue stragglers \( N_{\text{total}} \) and the fraction of the blue sequence \( N_{\text{blue}}/N_{\text{total}} \). The total number of blue stragglers ranges from 10 to 99, and the fraction of the blue sequence ranges from 60% to 70%. It is clear that the initial distributions of binaries are very important for determining the formation of blue stragglers from binary evolution. The uncorrelated mass-ratio distribution (set 3) or the nonconstant distribution of orbital separation (set 5) generates a smaller \( N_{\text{total}} \) and a larger \( N_{\text{blue}}/N_{\text{total}} \), as compared to simulation set 1. On the other hand, the rising mass-ratio distribution (set 2) or the IMF of Scalo (1986) generates a larger \( N_{\text{total}} \) and a smaller \( N_{\text{blue}}/N_{\text{total}} \). The total number of blue stragglers depends strongly on \( f_0 \), although the fraction of the blue sequence does not depend on \( f_0 \). Based on the observed results given by Ferraro et al. (2009) and Xin et al. (2015) (as shown in Figure 5), the observed values of \( N_{\text{total}} \) and \( N_{\text{blue}}/N_{\text{total}} \) are 49 and 49%, respectively (25 red-sequence stars and 24 blue-sequence stars).
The results of binary population synthesis can explain the observed total number of blue stragglers in M30, but fail to explain the fraction of the blue sequence in M30.

5. Discussion

5.1. The Fraction of the Blue Sequence

In our study, the fraction of the blue sequence cannot be reproduced by binary population synthesis. Our simulations predict that 60%–70% of the total blue stragglers should be observed in the blue sequence, while the observed blue sequence only contains 49% of the total blue stragglers in M30. If the contributions of direct stellar collision and binary merger to the blue sequence are considered, the problem is more challenging.

One possible explanation is mass loss during mass transfer, which has to be considered in our present study, or we would overestimate the fraction of blue stragglers in the blue sequence. As the examples show in Figure 7, we compare the relative regions of the progenitors for two sequences in the conservative and non-conservative cases (e.g., 50% of the transferred mass is assumed to be lost from the system). We find that for the non-conservative cases, the progenitor region of the blue sequence is reduced more remarkably, relative to the region of the red sequence. But we should note that the brightest blue stragglers are significantly fainter than shown in previous studies for the non-conservative assumption, since the accretor cannot increase mass to such a large degree. This may decrease the percentage of blue sequence in the binary scenario.

Another possible explanation is that the uncertainties in the distribution of binary parameters in globular clusters are important to binary population synthesis. The uncertainties do not change the appearance of the two blue-straggler sequences, as shown in Figure 6, but significantly alter the quantitative estimates of the total number of blue stragglers and the fraction of the blue sequence. At present, our results for binary population synthesis are based on the assumptions adopted in the field. It is very likely that dynamical interactions in globular clusters alter the parameter distribution of primordial binary populations. For example, the Heggie–Hills law (hard binaries get harder, Heggie 1975; Hills 1975) tends to make the binaries closer, and exchange encounters (which often eject the least massive of the three stars) are more likely to increase the mass ratio of binaries. Based on the initial distribution of binaries shown in Figure 4, these dynamical effects can decrease the fraction of the blue sequence by bringing the binary systems from Case B evolution to Case A evolution. Therefore, it is very important to understand these uncertainties in the distributions of binaries in globular clusters.

Our results do not rule out the contribution of dynamical interactions, especially core collapse, to the formation of the two blue-straggler sequences in M30. Our results show that binary evolution can produce a blue sequence below the “low-luminosity boundary,” but this sequence is not as tight as the blue sequence observed in M30. This tight blue-sequence may come from core collapse (Ferraro et al. 2009), which is limited to the time range for the formation of blue-sequence blue stragglers from binary evolution and direct stellar collision.

From the present results of binary evolution, we predict that the majority of binary-origin blue stragglers in the blue sequence should have a low-luminosity white-dwarf companion if they are not already disrupted due to dynamical interactions. However, not all blue stragglers in the red sequence are experiencing mass transfer, and some of them may also have a white-dwarf companion. Moreover, the blue sequence may show chemical anomalies (such as a significant depletion of carbon and oxygen), similar to the red sequence with O-depletion (Lovisi et al. 2013) because chemical anomalies are expected for the binary-origin blue stragglers (Chen & Han 2004; Ferraro et al. 2006; Jiang et al. 2014b), but not for the collision-origin blue stragglers (Lombardi et al. 1995). Future observations of the two sequences of blue stragglers should determine whether binary evolution can contribute to both sequences of blue stragglers in M30.

5.2. Comparisons with Previous Studies

Our results are consistent with previous theoretical studies. It has been indicated that binary evolution can produce blue stragglers below the “low-luminosity boundary” from binary mergers (Chen & Han 2008; Stepian & Kiraga 2015) and case B mass transfer (Lu et al. 2010). Lu et al. (2010) have shown that case B binary evolution can reproduce a bluer sequence of blue stragglers than case A binary evolution. Moreover, observations have shown that in the color–magnitude diagram of open cluster NGC 188, some binary blue stragglers are close to the ZAMS, as shown in Figure 1 of Mathieu & Geller (2009). So far, these observed blue stragglers have been interpreted as having a binary origin with white dwarf companions (Geller & Mathieu 2011; Gosnell et al. 2015), similar to the BS–WD binaries in our models.

Xin et al. (2015) investigated the binary origin of blue stragglers in M30 using a different version of Eggleton’s stellar evolution code. They showed that the binary models nicely match the observed blue sequence in M30, but cannot attain the observed location of the blue sequence. Their calculations missed the binary models that can produce blue stragglers in the blue sequence, maybe because their grid covered a larger range of primaries from 0.7 \( M_\odot \) to 1.1 \( M_\odot \), but with larger steps...
of 0.1 $M_\odot$. Moreover, their code stopped in some cases because of numerical instabilities that prevented them from following the complete evolutionary tracks of these systems (Xin et al. 2015).

5.3. A Special or Common Phenomenon in Globular Clusters?

We suggest that the age of M30 (13 Gyr) is not special for the formation of the two blue-straggler sequences in globular clusters from binary evolution, because the accretor stars with a white dwarf becomes inevitable when the mass transfer is finished. For example, a binary system with $M_0 = 1.0$ $M_\odot$ ($M_2 = 0.45$ $M_\odot$, $P_0 = 0.677$ day) can be located in the blue sequence at 8 Gyr, as shown in Figure 8, which suggests that the different primary masses of the binary may contribute to the blue stragglers in the blue sequence at various ages. Therefore, the appearance of two sequences produced by binary evolution may not be a short-lived phenomenon in globular clusters.

However, clearly separated sequences are not easy to observe. It should be noted that in the other two globular clusters (NGC 362 and NGC 1261), the gaps between the two sequences are much smaller than the widths of the blue sequence. This may be because of reddening variation, distance variation, observational error, etc. For example, the cores of globular clusters may be the most probable place to find two clearly separated sequences; within cores all blue stragglers can be thought to have the exact same distance and reddening, without the pollution from the blue stragglers in the outer region of a cluster that could have a slightly different reddening and distance modulus. Moreover, the photometric error needs to be significantly smaller than the shift for the companions in the color–magnitude diagram. Considering the subsequent evolution of blue-sequence blue stragglers, some of them may also appear to be between two sequences, e.g., the brightest blue-sequence blue straggler observed in M30 that is very close to the “low-luminosity boundary” (shown in Figure 5).

5.4. W UMa Contact Binaries in the Blue-straggler Region

Our simulations cannot take into account W UMa contact binaries because of the numerical difficulty of constructing their physical models, which is still one of the most important unsolved problems of stellar evolution (Eggleton 2006; de Mink et al. 2007; Eggleton 2010). However, Rucinski (2004) has shown that the total luminosity of W UMa contact binaries becomes more and more similar to that of the bright component in such binaries as the mass ratio decreases since the contribution from the faint component becomes smaller and smaller. Here, we roughly estimate their locations in the color–magnitude diagram as follows, using methods similar to those used by Rubenstein (2001) and Rucinski (2004). Observations show that the two components of these binaries have nearly equal surface effective temperatures ($T_1 = T_2 = T$), while their radius ratio is constrained by Roche geometry, $R_2/R_1 \approx (M_2/M_1)^{0.46}$ (Kuiper 1941). Their total surface luminosities are nearly equal to their total nuclear luminosities (e.g., Webbink 2003; Jiang et al. 2009). Considering the luminosity transfer between two components and the primaries still in the main sequence (Yakut & Eggleton 2005; Li et al. 2008), we can obtain the luminosities and effective temperatures of two components of contact binaries, and then obtain their combined magnitudes when these binaries are observed as one point.

Figure 9 shows the distribution of contact binaries with mass ratios $q = 0.1$, 0.3, 0.5, 0.7, 0.9 in the color–magnitude diagram, while the primary masses range from 0.91 $M_\odot$ to 1.44 $M_\odot$. These contact binaries become brighter and redder as the mass ratio increases, and this shift agrees with the results given by Rucinski (2004). These contact binaries with different mass ratios can cover the observed distribution of W UMa contact binaries in M30, and we find that the observed W UMa contact binary in the blue sequence corresponds to a smaller mass ratio (e.g., $q < 0.3$) than the two W UMa contact binaries in the red sequence (e.g., $q > 0.3$). This suggests that the W UMa contact binaries in both sequences of blue stragglers may be due to different mass ratios.

Moreover, we suggest that W UMa contact binaries could evolve from the red sequence to the blue sequence, when they evolve into systems with smaller mass ratios due to dynamical evolution (Li et al. 2008). At present, there are about a dozen W UMa systems with known mass ratios in globular clusters (e.g., Kallrath et al. 1992; McVean et al. 1997; Li & Qian 2013), and only half of them are located in the blue-straggler region. According to the color–magnitude diagram of NGC 6397 given by Kaluzny et al. (2006), the W UMa system V8 seems to be a blue-sequence blue straggler, and has a low mass ratio ($q = 0.159$, Li & Qian 2013). This may be consistent with our prediction.

Despite having similar binary evolution origins, W UMa contact binaries in M30 have different Roche-lobe-filling situations from other blue-straggler binaries. For other blue-straggler binaries, binaries in the red sequence are semi-detached or detached BS–WD binaries, while those in the blue sequence are mainly detached BS–WD binaries. However, W UMa contact binaries can appear at different sequences in the color–magnitude diagram for similar reasons as other...
blue-straggler binaries. This happen because the contributions of less massive companions are different when they are observed as a single star. Therefore, the binary scenario is not incompatible with the observed W UMa contact binaries in M30.

6. Conclusions

In this paper, we explore the possibility that binary evolution contributes to the formation of blue stragglers in two sequences in globular cluster M30. Our results show that the primordial binaries may contribute to the blue sequence of blue stragglers in M30. Considering W UMa contact binaries observed in both sequences, the possibility of binary evolution having contributions to both sequences should not be ruled out. We suggest that this feature, a blue sequence with a much wider red sequence, may not be uncommon among globular clusters. However, the observed fraction of the blue sequence cannot be reproduced by studies of binary population synthesis with the initial distribution of field binaries, which suggests that the initial distribution of binaries in globular clusters may be modified by dynamical interaction or be very different from that in the field.

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