A SYSTEMATIC STUDY OF EFFECTS OF STELLAR ROTATION, AGE SPREAD, AND BINARIES ON COLOR–MAGNITUDE DIAGRAMS WITH EXTENDED MAIN-SEQUENCE TURNOFFS

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ABSTRACT

Stellar rotation, age spread, and binary stars are thought to be the three most possible causes of the peculiar color–magnitude diagrams (CMDs) of some star clusters, which exhibit extended main-sequence turnoffs (eMSTOs). The answer is far from clear. This paper studies the effects of the three above causes on the CMDs of star clusters systematically. A rapid stellar evolutionary code and a recently published database of rotational effects of single stars have been used, via an advanced stellar population synthesis technique. As a result, we find a similar result for rotation to recent works, which suggests that rotation is able to explain, at least partially, the eMSTOs of clusters, if clusters are not too old (<2.0 Gyr). In addition, an age spread of 200–500 Myr reproduces extended turnoffs for all clusters younger than 2.5 Gyr, in particular, for those younger than 2.2 Gyr. Age spread also results in extended red clumps (eRCs) for clusters younger than 0.5 Gyr. The younger the clusters, the clearer the eRC structures. Moreover, it is shown that binaries (including interactive binaries) affect the spread of MSTOs slightly for old clusters, but they can contribute to the eMSTOs of clusters younger than 0.5 Gyr. Our result suggests a possible way to disentangle the roles of stellar rotation and age spread, i.e., checking the existence of CMDs with both eMSTOs and eRCs in clusters younger than 0.5 Gyr.

Key words: galaxies: star clusters: general – Hertzsprung–Russell and C–M diagrams – stars: evolution

1. INTRODUCTION

Color–magnitude diagrams (CMDs) with extended main-sequence turnoffs (eMSTOs), which were observed by Hubble Space Telescope (HST) in the star clusters of the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC), have received much attention in recent years. Such CMDs challenge the widely accepted thoughts on star clusters, i.e., simple stellar populations (SSPs) with a single age and metallicity (Mackey & Broby Nielsen 2007; Mackey et al. 2008; Girardi et al. 2009; Milone et al. 2009; Piatti 2013). Great efforts have been made to explain the observations. Many factors are thought to be the reasons for the observed eMSTOs, including a spread of chemical abundance (Piotto et al. 2005, 2007; Mackey et al. 2008; Goudfrooij et al. 2009), capture of field stars (Mackey et al. 2008; Goudfrooij et al. 2009), merger of existing star clusters (Mackey & Broby Nielsen 2007), formation of a second generation of stars from the ejecta of first-generation asymptotic giant branch stars (D’Ercole et al. 2008; Goudfrooij et al. 2009), binary stars (e.g., Milone et al. 2009; Yang et al. 2011), observational selection and uncertainty effects (Keller et al. 2011), mixture of stars with and without overshooting (Girardi et al. 2011), differential reddening (Platais et al. 2012), age spread (e.g., Girardi et al. 2011; Rubele et al. 2011; Richer et al. 2013), stellar rotation (e.g., Bastian & de Mink 2009), and a combination of binaries and rotation (Li et al. 2012a). A spread of age (Milone et al. 2010; Girardi et al. 2011), rotation (Bastian & de Mink 2009), and a combination of rotation and binaries (Li et al. 2012a) are finally thought of as the three most possible causes of the special CMDs, although some contrasting points are insisted by other works, such as Mucciarelli et al. (2008), Goudfrooij et al. (2011a, 2011b), Glatt et al. (2008), Rubele et al. (2010), and Girardi et al. (2013). The work of Li et al. (2015a) indicates a degeneracy of the effects of stellar binarity and rotation.

Recently, many works have investigated the effects of some possible factors separately. In particular, stellar rotation has been widely considered (e.g., Yang et al. 2013; Goudfrooij et al. 2014; Jiang et al. 2014; Li et al. 2014; Brandt & Huang 2015; D’Antona et al. 2015; Niederhofer et al. 2015; Bastian et al. 2016). Yang et al. (2013) studied the effect of rotation on massive stars via their own stellar model. They concluded that rotation does not affect the CMD of star clusters younger than about 0.7 Gyr. A limitation of that work is that binary evolution was not taken into account, and a comparison to the effects of age spread and binaries was not made. However, an opposite conclusion was gained later by Brandt & Huang (2015), who took the stellar model of Georgy et al. (2013) and considered gravity darkening. The works of Niederhofer et al. (2015) and D’Antona et al. (2015) also give support to the conclusion of Brandt & Huang (2015), but binary evolution was not taken into account either. Li et al. (2014) declare that NGC 1651 is a genuine SSP from the observational thickness of the subgiant branch, but Li et al. (2015a) and, in particular, Li et al. (2015b) brought forward some doubts about this according to the best-fit results based on detailed CMD comparisons. Correnti et al. (2014) also suggest that age spread can better explain some CMDs than rotation. In this case, whether the peculiar CMDs of star clusters result from stellar rotation remains unclear (Bastian et al. 2016; Niederhofer et al. 2016). More works on the causes of eMSTOs and stellar population types of star clusters are needed. In addition, most star clusters possibly contain a lot of binaries, and the effects of binary evolution, rotation, and age spread are somewhat degenerate (Li et al. 2015a). Thereby, in order to explain the observed CMDs of star clusters in the correct way, it is necessary to study the effects of stellar rotation, binary...
evolution, and age spread simultaneously. This work therefore revisits the effects of the above three factors on the CMDs of clusters with various ages. Besides the application of a new population synthesis technique (Li et al. 2015a), another improvement of this work is that a few thousand stars are assumed for each cluster, which leads to comparable star numbers to the most observed CMDs with eMSTOs. Finally, the roles of stellar rotation, age spread, and resolved and unresolved binaries are shown clearly and compared to each other.

The layout of the paper is as follows: In Section 2, we outline the model assumptions and computation techniques. Then we show the effects of rotation, binaries, and age spread in Sections 3–5, respectively. We give our conclusions in Section 6.

2. MODEL ASSUMPTIONS AND COMPUTATION TECHNIQUES

In order to model the CMDs of star clusters in detail, we use an advanced stellar population synthesis (hereafter ASPS) technique, which was brought forward by Prof. Zhongmu Li and has taken into account stellar binarity, rotation, star formation history, and observational uncertainties simultaneously (Li et al. 2015b). The model assumptions and computation techniques are introduced as follows.

2.1. Initial Mass Function (IMF)

Following some previous works (e.g., Li & Han 2008a, 2008b; Li et al. 2012b, 2015a), we take the IMF of Salpeter (1955) \( f(m) \propto m^{-2.35} \) for stellar population models. This IMF is widely used in all kinds of stellar population synthesis studies. The lower and upper mass limits of stars are set to 0.1 and \( 100 \, \text{\(M_{\odot}\)} \), respectively, as stars with masses out of this range are too faint or evolve too fast to be observed. Although the Salpeter IMF is not so accurate for low-mass \( (<1 \, \text{\(M_{\odot}\)}\) ) stars, it will not affect the result because only bright CMD parts are used in this work.

![Figure 1](image1.png)

**Figure 1.** Fitting distributions of rotation rates \( (\omega > 0.05) \) of B9- to F2-type stars. The fitting formulae are based on the results of Royer et al. (2007) and are described in Table 1. \( p \) and \( \omega \) are star fraction and rotation rate, respectively. This paper uses the B9 distribution for more massive stars.

![Figure 2](image2.png)

**Figure 2.** Synthetic CMD of a single star stellar population with metallicity \( (Z) \) of 0.008 and age of 1 Gyr. The rotation effect of stars more massive than 1.6 \( M_{\odot} \) is considered. All stars are assumed to follow the RRD of Royer et al. (2007).

| Type     | \( f_0 \) | \( a_1 \) | \( w_1 \) | \( c_1 \) | \( a_2 \) | \( w_2 \) | \( c_2 \) |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| B9–A1    | 0         | 0.91994   | 0.85301   | 0.62004   | 0.11451   | 0.07828   | 0.13371   |
| A0–A1    | 0         | 0.29196   | 0.25220   | 0.20447   | 0.61923   | 0.61374   | 0.67926   |
| A2–A3    | -0.99083  | 0.12616   | 0.22893   | 0.06704   | 1.99339   | 0.84887   | 0.59142   |
| A4–A6    | 0         | 0.21978   | 0.12983   | 0.49718   | 0.60092   | 0.33494   | 0.70526   |
| F0–F2    | 0         | 0.06730   | 0.06988   | 0.10557   | 0.75391   | 0.45133   | 0.55747   |
| A7–A9    | 0         | 0.02195   | 0.02689   | 0.07078   | 0.01771   | 0.03942   | 0.20553   |
|          | \( a_3 \) | \( w_3 \) | \( c_3 \) | \( a_4 \) | \( w_4 \) | \( c_4 \) |
|          | 0         | 0.10796   | 0.08934   | 0.41528   | 0.65859   | 0.29589   | 0.66827   |

**Note.** All distributions are described by \( \frac{dp}{d\omega} = f_0 + \sum_{i} a_i \exp\left(-2 * \left(\frac{\omega - c_i}{w_i}\right)^2\right) \), where \( p \) is star fraction and \( \omega \) is rotation rate.
2.2. Star Sample

We build up stellar populations based on a series of basic SSPs with half single stars and half binaries. Each basic SSP contains 100,000 components. The star sample of basic populations is generated as follows. The mass of the primary component of a binary is generated following the selected IMF, and the mass of the secondary component is then calculated by taking a random secondary-to-primary mass ratio \( q \), which obeys a uniform distribution within 0–1. Because eccentricity affects stellar evolution slightly (Hurley et al. 2002), a random eccentricity \( e \) within 0–1 is assigned to each binary. The separations \( a \) of two binary components are given by a simple shape:

\[
    a_n(a) = \begin{cases} 
        \alpha_{\text{sep}} (a/a_0)^m & a \leq a_0, \\
        \alpha_{\text{sep}} & a_0 < a < a_1,
    \end{cases}
\]

where \( \alpha_{\text{sep}} \approx 0.070, a_0 = 10 \ R_\odot, a_1 = 5.75 \times 10^4 R_\odot = 0.13 \text{ pc}, \) and \( m \approx 1.2 \) (Han et al. 1995). This process leads to about 50% binaries with orbital periods less than 100 yr in a simple population. We call such simple populations basic models and build up other stellar populations based on these models. This method is used by many previous works, e.g., Zhang et al. (2004) and Li & Han (2008b).

Because the binary fraction is different for various star clusters, we build stellar populations with different binary fractions. In a simple way, we change the binary fraction of a population by removing some random single stars or binaries from basic models. This allows one to build stellar populations with arbitrary binary fractions between 0% and 100% easily. Note that all stars with orbital periods larger than 100 yr are considered as single stars, as their components hardly exchange mass in their evolution (Hurley et al. 2002).

**Figure 3.** Effects of rotating stars and binaries on CMDs of simulated star clusters. Color and magnitude are in mag. All clusters have the same metallicity \((Z = 0.008)\) and age \((0.2 \text{ Gyr})\). Stars of each cluster (about 6000 stars) formed in a single starburst. Binary fractions \( f_b \) in the left, middle, and right columns are 0.3, 0.5, and 0.7, respectively. From top to bottom, the fraction of rotating stars \( f_r \) increases. “rot-bsSSP” means SSP with a fraction of rotating stars (including binary and single stars). “eMSTO” denotes extended main-sequence turnoffs. “BS” and “RS” mean blue stragglers and red stragglers, respectively. Binaries closer than 2500 AU are assumed to be unresolved. This separation corresponds to 0.005 (approximately HST resolution) at a distance of 50 kpc.
2.3. Stellar Evolution

After the generation of a star sample, we evolve all stars using the rapid stellar evolution code of Hurley & Tout (1998) and Hurley et al. (2002) (Hurley code). This code calculates the evolution of stars using some fitting formulae, which are based on the stellar models computed by Pols et al. (1998). Many stellar evolutionary parameters, e.g., effective temperature, surface gravity, and luminosity, can be computed by the Hurley code. There are two advantages to using the Hurley code for this work. First, the evolution of both single and binary stars can be calculated via this code. Most binary interactions, such as mass transfer, mass accretion, common-envelope evolution, collisions, supernova kicks, angular momentum loss mechanism, and tidal interactions, are taken into account in its binary evolution mode. Second, it allows one to calculate the evolution of stars much faster than traditional stellar evolutionary codes, but with enough accuracy (less than 5% in stellar luminosity, radius, and core mass) for population synthesis works. Some default parameters of the Hurley code, which have been tested by Hurley & Tout (1998) and Hurley et al. (2002), are used for this work. Because binary evolution changes both the evolutionary tracks and main-sequence lifetimes of stars and will directly change the CMDs of star clusters, it is necessary to include binary evolution in CMD studies. We will show that binary evolution is helpful for understanding the eMSTOs of clusters younger than 0.5 Gyr because some scattered stars form in this evolution mode. Therefore, it is appropriate to choose the Hurley code for this work. For convenience, a metallicity of $Z = 0.008$ is taken for simulated clusters.

2.4. Treatment of Stellar Rotation

The Hurley code does not take stellar rotation into account, so we add the effect of rotation on effective temperature and luminosity to some stars in the mass range of 1.6–15 $M_\odot$ when necessary. This allows us to study star clusters younger than about 2 Gyr, in which CMDs with eMSTOs are usually observed. Because the database of Georgy et al. (2013) does not include stars less massive than 1.7 $M_\odot$, the effect of rotation on stars between 1.6 and 1.7 $M_\odot$ is simply interpolated by...
assuming zero effect for $1.6 \, M_\odot$. However, in order to give a reliable conclusion, only the results of clusters younger than 1.7 Gyr are used for this paper.

2.4.1. Inclusion of Rotation Effect

A recent result of Georgy et al. (2013) is chosen for calculating the effect of rotation, because this database is particularly designed for constructing synthetic stellar populations. The database is derived from the Geneva code, which includes a full parameterization of angular momentum transport and wind loss. This database has been used by many previous works, such as Li et al. (2015a) and Brandt & Huang (2015). The procedure to include the rotation effect is as follows. First, the changes of surface temperature and luminosity, which are caused by stellar rotation, are calculated by comparing the evolutionary tracks of rotating stars to those of their nonrotating counterparts. These changes depend on metallicity, mass, rotation rate, and age. Then such changes are added to the evolutionary parameters of nonrotating stars, which are computed via the Hurley code. A limitation in the database of Georgy et al. (2013), i.e., the stellar mass range of $1.7–15 \, M_\odot$, should be noted, as it makes us unable to study the rotational effect on clusters older than about 1.7 Gyr reliably. Because the database of Georgy et al. (2013) does not contain the cases for some masses, metallicities, rotation rates, and ages, the original values are interpolated to match our needs. Note that the effect of rotation on the main-sequence lifetimes of stars is naturally included in our treatment. The reason is that the database of Georgy et al. (2013) has given the change of evolutionary parameters caused by rotation at various ages. The changes of main-sequence lifetimes can be described by the evolutionary parameters. For example, on the Hertzsprung–Russell diagram, a rotating star will be shown to get a turnoff point at an older age compared to its nonrotating counterpart. Thereby, when we correct for the evolutionary parameters of rotating stars, the effect of rotation on main-sequence lifetime has been included. However, unlike the work of Brandt & Huang (2015), gravity darkening has not been accounted for in this work. According to a test of Dr. Timothy D. Brandt (later Brandt), this affects

![Figure 5](https://example.com/figure5.png)

Figure 5. Similar to Figure 3, but for simulated star clusters with an age of 0.5 Gyr.
our result slightly, although gravity darkening leads to a small extra extension of turnoffs.

2.4.2. Rotation Rate Distribution

In order to calculate the effects of stellar rotation on the synthetic CMDs of simulated star clusters properly, we need to assume a distribution of stellar rotation rate \( \left( \omega = \Omega / \Omega_{\text{crit}} \right) \) (RRD), which obviously affects the CMD parts near the MSTO. Fortunately, the works of Royer et al. (2007) and Zorec & Royer (2012) have determined the statistical distributions of B9- to F2-type stars. This enables us to assign random rotation rates to the member stars of a population directly following some observational distributions rather than a theoretical one. For the sake of convenient use of the observed distributions, we fitted the results of Royer et al. (2007) (hereafter Royer distribution) via some polynomial functions (see Figure 1 and Table 1) and then use these functions to represent the RRDs of B9–F2 stars. The comparison of fitting distributions to the original results of Royer et al. (2007) indicates that these fitting functions can reproduce the observed distributions accurately. Stars of earlier types than B9 \( (\gtrsim 2.5 \, M_\odot) \) are assumed to have the same RRD as the Royer result for B9 stars. An obvious trend is that the fraction of stars decreases quickly with increasing rotation rate for \( \omega > 0.7 \). This means that there are only a small fraction of stars with \( \omega > 0.7 \). Note the results will be similar if the more recent result of Zorec & Royer (2012) is used instead of Royer et al. (2007), because these two works, in fact, give similar distributions for the stellar rotation rate and rotational velocity of stars.

2.5. Atmosphere Library

The stellar evolutionary parameters ([Fe/H], \( T_{\text{eff}}, \log g, \log L \)) are transformed into colors and magnitudes via the atmosphere library of Lejeune et al. (1998) (BaSeL). Because this wide-wavelength band coverage (including the well-used \( B, V, I, \) and \( K \)) library was well calibrated and has been widely used in a good deal of research works, it is an excellent choice for this work.
3. EFFECT OF STELLAR ROTATION

It is necessary to check the reliability of the treatment of stellar rotation first, as the combination of results from Hurley et al. (2002) and Georgy et al. (2013) is used. Our test finally shows that the treatment of rotation in this work is in good agreement with other works, e.g., Brandt & Huang (2015). Figure 2 shows a CMD of a simulated cluster with $Z = 0.08$ and 1.0 Gyr. The RRD of Royer et al. (2007) is taken for this cluster, and all stars are assumed to be single stars. We see that this CMD is close to the result of Brandt & Huang (2015).

Figures 3–10 then show the effect of rotation on the CMDs of simulated star clusters with various ages from 0.2 to 1.7 Gyr. Three binary fractions ($f_b = 0.3$, 0.5, and 0.7) are taken for clusters on account of the existence of binaries in most young and intermediate-age clusters (e.g., Elson et al. 1998). In addition, we vary rotator fraction ($f_r$) from 0 to Royer distribution because some star clusters without eMSTOs have been observed, and such clusters may contain fewer rotating stars than the results of Royer et al. (2007). In fact, the RRD of stars in the LMC clusters is unknown, and it is possible that some star clusters include more rotating stars than the observations of Royer et al. (2007). We therefore enlarge the fraction of stars with a large rotation rate by taking a Gaussian distribution with a mean and standard deviation of 0.7 and 0.1, respectively, for the rotation rate (hereafter Gaussian distribution). As a whole, four rotator fractions ($f_r$), i.e., 0, 0.5 Royer, Royer, and Gaussian, are finally adopted for simulated star clusters. The models with $f_r = 0$ contain no rotating stars. Those with $f_r = 0.5$ Royer contain half nonrotating stars and half stars with rotation rates following the Royer distribution. For the case of $f_r = $ Royer, all stars obey the Royer distribution. Taking various rotator fractions will produce various kinds of CMDs, and this is helpful for understanding the role of rotation clearly. In order to enable readers to compare the figures, Figures 3–10 are plotted with the same size. Observational errors are not considered to avoid confusion.

Figures 3 and 4 show the effect of rotating stars on the CMDs of young (0.2 and 0.4 Gyr) star clusters. When binary fraction is small (0.3), stellar rotation leads to only a narrow eMSTO for clusters of 0.2 Gyr, while it extends the MSTO of...
clusters of 0.4 Gyr or more. At the same time, binaries (including both resolved and unresolved ones) supply significant extension on the turnoff of such clusters. Obvious eMSTO structures are formed by including a large fraction (e.g., 0.7) of binaries. In particular, eMSTOs become clearer when both binaries and rotating stars are included.

Figures 5 and 6 give the result for some clusters with ages of 0.5 and 0.8 Gyr. We see that rotation results in eMSTOs. The extension of MSTO is obviously larger than in the cases of 0.2–0.4 Gyr, and it increases with stellar age. Moreover, the extension of MSTO seems very sensitive to RRD. The second case of rotation, $f_\text{rot} = 0.5$ Royer, leads to the largest extension. Binaries are shown to be much less important to the formation of eMSTOs, although a few scattered stars are generated from binaries.

Figures 7 and 8 present the results for 1.0 and 1.2 Gyr old simulated clusters, respectively. The CMDs of populations with rotators become significantly different from those of populations of nonrotating stars. If only the effect of binary stars (including resolved and unresolved binaries) is taken into account, MSTOs are very thin (top panels), although some scattered stars (e.g., blue stragglers and red stragglers) are generated. The turnoffs become significantly thick when some rotators are included in star clusters. In particular, maximum eMSTOs are observed in clusters containing half rotating stars following the RRD of Royer et al. (2007). Large eMSTOs can also be observed when taking the Royer distribution for all stars. One can look at the two middle rows of Figures 7 and 8 for details. For these clusters, their CMD parts near turnoff look like a “golf club” (Girardi et al. 2011), in which the part above the turnoff point is wider than the lower part in color direction. The synthetic CMDs are similar to those observed in many star clusters, e.g., NGC 1399.

Figures 9 and 10 show the cases of simulated clusters with ages of 1.5 and 1.7 Gyr, respectively. Similar to previous figures, we have shown that stellar rotation is able to generate eMSTOs. However, the extension of MSTOs becomes smaller compared to clusters with ages around 1.1 Gyr (Figures 7 and 8).

It is seen from the above results that overall stellar rotation has some effect on the CMDs of clusters between 0.2 and 1.7 Gyr, but the effect depends on stellar age. The effect of
rotation on MSTO increases with age from 0.2 to about 1.2 Gyr, and then it decreases with increasing age. The result is similar to the work of Brandt & Huang (2015). Rotation makes both the turnoff and main sequence near turnoff wider than the nonrotating case. For simulated clusters with ages between 1.0 and 1.5 Gyr, the CMD part including turnoff and main sequence looks like a “golf club” (see, e.g., 0.5 Royer), which is similar to the observed results of many clusters, e.g., NGC 1651, NGC 1868, and NGC 1399. Therefore, stellar rotation is able to reproduce, at least partially, the MSTOs of star clusters. Our conclusion agrees well with the works of Brandt & Huang (2015), D’Antona et al. (2015), and Niederhofer et al. (2015), but is partially different from that of Yang et al. (2013). The different conclusion of Yang et al. (2013) for young clusters possibly results from their stellar evolution model. Note that if the gravity-darkening effect is considered, the results will be more similar to the observed CMDs, because the gravity-darkening effect can slightly extend MSTOs, according to the test of Brandt.

From this work, we find that the role of rotation depends on many factors, e.g., stellar evolution model, RRD, and the mass range of rotating stars. In more detail, some opposite results will be obtained from the stellar evolution models of Yang et al. (2013) and Georgy et al. (2013). RRD affects the CMD shapes of simulated clusters significantly (see Figures 6–8), and considering stars less massive than 1.7 $M_\odot$ or not leads to various roles of rotation for clusters older than about 1.7 Gyr. This therefore calls for more works on these factors, in order to unfold the stellar populations of star clusters with MSTOs. However, gravity darkening does not significantly affect our main conclusions.

4. EFFECT OF BINARY STARS

Some previous works (e.g., Li et al. 2014, 2015a) have mentioned that binary stars are not the main cause of MSTOs, but no work supplies a clear figure about the effects of different types of binaries. Figures 3 and 4 suggest that
resolved and unresolved binaries may contribute to the eMSTOs of young (<0.5 Gyr) clusters. Binary stars lead to some blue stragglers (scatters on the upper left of the turnoff, e.g., BS in Figure 3), red stragglers (scatters on the lower right of the turnoff, e.g., RS in Figure 3), and scattered stars above the turnoff (e.g., Figures 9 and 10). However, the role of binaries depends on stellar age. For clusters older than 0.5 Gyr, scattered stars from binaries affect the turnoff shape very slightly (Figures 5–10). This implies that binaries are certainly not the main cause of eMSTOs of most intermediate-age clusters. As a part of binaries, resolved or interactive binaries are correspondingly not the main cause of eMSTOs. The top panels of Figures 9 and 10 show the effect of unresolved binaries in a clearer way. It is obvious that unresolved binaries (black stars in region “A”) make the main sequence wider compared to a population of single stars (red points), as some unresolved binaries are located on the right of the main sequence. In addition, a few unresolved binaries are located above the turnoff (region “B”). However, the turnoff structure of a population of nonrotating binaries is obviously different from the observed CMDs, because such binary populations contain few stars in region “C” but many stars are observed in star clusters with peculiar CMDs. Such stars are actually an important part of eMSTOs. Therefore, binaries, including interactive binaries, resolved binaries, and unresolved binaries, are not the main cause of eMSTOs, although they can contribute to the eMSTOs of clusters younger than 0.5 Gyr.

5. EFFECT OF AGE SPREAD

In this section, we study the effect of age spread on the CMDs of star clusters with various ages. We assume that clusters form their stars within 200–500 Myr and the binary fractions \((f_b)\) of them change from 0.3 to 0.7. The ages of the youngest stars in clusters are used as stellar population ages, and they are given between 0.2 and 2.5 Gyr. As some examples, the main results are presented in Figures 11–17. Note that only a few separated starbursts with age intervals of 100 Myr are taken for building composite stellar populations,
but the star formation of real clusters could be continuous bursts. A homogeneous star formation history is assumed for all simulated clusters, although it is possibly different for real clusters. This results in separated isochrones, and the figures look somewhat different from the CMDs caused by rotation (Figures 3–10). In addition, the age spread of most star clusters younger than 0.8 Gyr is possibly less than about 40%, but in order to supply some comparisons with older clusters, the CMDs with spreads up to 500 Myr are shown here. This is helpful for better understanding the dependence of the effect of age spread on stellar age, as well as the difference between the effects of age spread and rotation.

We find that age spread has a significant effect on the CMDs of all clusters younger than 2.0 Gyr (Figures 11–16). The main effect of age spread is to thicken the MSTO part. In detail, the turnoff of a cluster with multiple starbursts has obviously spread in both color and magnitude, which is obviously different from that of an SSP of stars with the same metallicity and age (see top panels of Figures 3–10 for comparisons). As we see, the shape of the CMD part consisting of main sequence and turnoff looks like a “golf club,” if a cluster is younger than 2.0 Gyr and has age spreads larger than 200 Myr. However, we see that an age spread less than 500 Myr affects the CMDs of clusters older than about 2.5 Gyr slightly (Figure 17). Even though an age spread of 500 Myr is assumed, the turnoffs of clusters with ages of 2.5 Gyr are similar to those of simple populations if the typical observational errors (∼0.014 mag) in color and magnitude are taken into account.

We can conclude from Figures 11–17 that age spread does not obviously affect the thickness of the main-sequence part below turnoff, for all ages. This is a key difference between the effects of age spread and stellar rotation, because besides the turnoff part, rotation widens the main sequence fainter than the turnoff, as shown in, e.g., Figures 4–6. This is possibly useful for checking whether age spread exists in clusters.

Meanwhile, we observe that age spread leads to obvious eRCs (Figures 11 and 12) for clusters younger than 0.5 Gyr. This is clearly different from the effect of stellar rotation (see Figures 3 and 4 for comparison) and implies that we can possibly check the existence of age spread from the shapes of red clumps of star clusters.

**Figure 11.** Effects of age spread and binary fraction on CMDs of simulated star clusters. All clusters have the same metallicity ($Z = 0.008$). No rotating star is included in these clusters, and binaries closer than 2500 AU are assumed to be unresolved. The age of the latest starburst (i.e., youngest population component) is assumed to be 0.2 Gyr. “t” gives the age ranges of stars. From top to bottom panels, age spread is different from 200 to 500 Myr. eMSTO and eRC mean extended main-sequence turnoff and extended red clump, respectively. Binary fractions ($f_b$) in left, middle, and right columns are 0.3, 0.5, and 0.7, respectively. “norot-bsCSP” means CSP consisting of nonrotating binaries and single stars.
Figure 12. Similar to Figure 11, but for simulated star clusters with a youngest population component of 0.4 Gyr.

Figure 13. Similar to Figure 11, but for simulated star clusters with a youngest population component of 0.5 Gyr.
Figure 14. Similar to Figure 11, but for simulated star clusters with a youngest population component of 1.0 Gyr.

Figure 15. Similar to Figure 11, but for simulated star clusters with a youngest population component of 1.5 Gyr.
Figure 16. Similar to Figure 11, but for simulated star clusters with a youngest population component of 2.0 Gyr.

Figure 17. Similar to Figure 11, but for simulated star clusters with a youngest population component of 2.5 Gyr.
6. CONCLUSION

This paper investigates the effects of stellar rotation, age spread, and binary stars on the CMDs of simulated star clusters with various ages, via the ASPS technique. It appears that binary stars are not the main cause of eMSTOs of most clusters older than 0.5 Gyr, although a few blue stragglers and red stragglers are produced by binary evolution, and unresolved binaries widen the main sequence toward redder color. However, binaries seem important for the eMSTOs of younger (e.g., <0.5 Gyr) clusters. Meanwhile, stellar rotation is able to explain, at least partially, the eMSTOs of clusters. Rotation can somewhat widen the turnoffs of clusters younger than 0.5 Gyr and extends the turnoffs of clusters between 0.5 and 1.7 Gyr significantly. Because the rotation effect of stars outside the mass range of 1.6–15 M⊙ is not taken into account, this work does not study the effect of rotation on the CMDs of clusters older than 1.9 Gyr. Rotation seems unlikely to form CMD shapes like a “golf club” in clusters significantly older than about 1.9 Gyr, because the turnoff stars of such clusters, which are less massive than 1.6 M⊙, usually rotate much more slowly, and the effect of rotation decreases with increasing age from about 1.2 Gyr (see also Brandt & Huang 2015). This agrees well with the observational result, i.e., there is little evidence for eMSTOs in clusters of 2 Gyr in age or older. If less massive stars (e.g., those between 1.0 and 1.6 M⊙) are considered, rotation widens the main-sequence part below turnoff for all simulated clusters. In addition, age spread can reproduce eMSTOs for all clusters younger than 2.5 Gyr, but it does not obviously affect the thickness of the main-sequence part fainter than turnoff. In particular, age spread results in “golf club” shapes in the regions near turnoff for all clusters from about 1.0 to 2.2 Gyr (tested but not shown in this paper). It also results in a significant extension of the red clumps (eRC) of clusters younger than 0.5 Gyr. As a whole, the effects of binary stars and stellar rotation depend on stellar age, obviously.

It can be concluded that the eMSTOs of clusters younger than 0.5 Gyr possibly result from age spread or a combination of binaries and stellar rotation. The eMSTOs of older clusters may be caused mainly by age spread or stellar rotation. It is also possible that the observed features are related to all three factors.

Although we have used the recent results of Georgy et al. (2013) to calculate the effects of rotation on luminosity and surface temperature of stars, some uncertainties still remain. This may somewhat affect the synthesized CMDs. Our conclusion of the effect of stellar rotation agrees well with recent works such as Brandt & Huang (2015), Niederhofer et al. (2015), and Milone et al. (2016). Even if another database of rotating stars (e.g., Ekström et al. 2012) is used instead of Georgy et al. (2013), the results will be similar, because the two databases are from the same code. Note that although the works of Bastian & de Mink (2009), Ekström et al. (2012), and Georgy et al. (2013) suggest the possibility of rotation to explain eMSTOs of star clusters, the rotation effect of two recent works, i.e., Ekström et al. (2012) and Georgy et al. (2013), is different from that of Bastian & de Mink (2009) (see Brandt & Huang 2015). Besides the stellar evolutionary models, RRD affects the final CMDs evidently. This calls for accurate distributions for clusters in the LMC and SMC. Moreover, this work considers the effects of binaries and rotating stars separately, but they are actually related. Although such treatment is reasonable by now due to the lack of a stellar evolutionary code, in which both binaries and rotation have been taken into account, it is certainly necessary to check the results using some new codes in the future.

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