COMBINED EFFECTS OF BINARIES AND STELLAR ROTATION ON THE COLOR–MAGNITUDE DIAGRAMS OF INTERMEDIATE-AGE STAR CLUSTERS

ZHONGMU LI\textsuperscript{1,2}, CAIYAN MAO\textsuperscript{1}, LI CHEN\textsuperscript{1}, AND QIAN ZHANG\textsuperscript{1}

\textsuperscript{1} Institute for Astronomy and History of Science and Technology, Dali University, Dali 671003, China; zhongmu.li@gmail.com
\textsuperscript{2} National Astronomical Observatories, Beijing 100012, China

Received 2012 October 10; accepted 2012 November 1; published 2012 December 3

ABSTRACT

About 70\% of intermediate-age star clusters in the Large Magellanic Clouds have been confirmed to have broad main sequence, multiple or extended turnoffs, and dual red giant clumps. The observed result seems to be at odds with the classical idea that such clusters are simple stellar populations. Although many models have been used to explain the results via factors such as prolonged star formation history, metallicity spread, differential reddening, selection effect, observational uncertainty, stellar rotation, and binary interaction, the reason for the special color–magnitude diagrams is still uncertain. We revisit this question via the combination of stellar rotation and binary effects. As a result, it shows “golf club” color–magnitude diagrams with broad or multiple turnoffs, dual red clumps, blue stragglers, red stragglers, and extended main sequences. Because both binaries and massive rotators are common, our result suggests that most color–magnitude diagrams, including extended turnoff or multiple turnoffs, can be explained using simple stellar populations including both binary and stellar rotation effects, or composite populations with two components.

Key words: binaries: general – galaxies: star clusters: general – globular clusters: general – stars: rotation

1. INTRODUCTION

Star clusters are usually assumed to be simple stellar populations (SSPs) in which all stars formed in a short timescale and with the same metallicity. The color–magnitude diagram (CMD) of a star cluster should be similar to an SSP isochrone. However, recent observations based on the data obtained with the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST) showed double, multiple, or extended main sequence turnoffs (MSTOs), and dual clumps of red giants (RCs) for many intermediate-age star clusters in the Large Magellanic Cloud (LMC), e.g., NGC 1751, NGC 2108, NGC 1846, NGC 1806, and NGC 1783. The CMDs near turnoff are shaped like a golf club (hereafter golf club shape). For more details, one can refer to, for example, Bertelli et al. (2003), Piotto et al. (2005, 2007), Milone et al. (2009, 2010), Mackey & Broby Nielsen (2007), Mackey et al. (2008), Goudfrooij et al. (2009), Bastian & de Mink (2009), Girardi et al. (2011), and Rubele et al. (2011).

Different models have been used for interpreting the special CMDs. For example, Mackey et al. (2008) and Goudfrooij et al. (2009) explained this by the spread of chemical abundance, but it is in disagreement with the similarity of metallicity of all stars (Mucciarelli et al. 2008; Goudfrooij et al. 2011a, 2011b). Then, Mackey et al. (2008) and Goudfrooij et al. (2009) interpreted this by the capture of field stars. This reproduces extended MSTO but has difficulty explaining double or multiple MSTOs (MMSTOs), which were found by, e.g., Glatt et al. (2008). Similarly, a picture based on the merging of existing star clusters had been brought forward (Mackey & Broby Nielsen 2007), but it seems to be uncommon that clusters in a normal molecular cloud would merge with each other (Goudfrooij et al. 2009). A scenario of formation of a second generation of stars from the ejecta of the first generation asymptotic giant branch stars was suggested, but it also has some disadvantages (D’Ercole et al. 2008; Goudfrooij et al. 2009). Bastian & de Mink (2009) studied this problem using the effect of rotation on the effective and surface gravity of stars, and then on the color and magnitude of star clusters. This model reproduced the double or multiple population, but Rubele et al. (2010) and Girardi et al. (2011) argued that the effect of stellar rotation alone could not explain the golf club shape of MSTOs. Instead, they suggested that a prolonged star formation history would explain the CMD with a golf club shape (Girardi et al. 2011). An age spread of about 300 Myr is needed to explain golf-club-shaped CMDs, including both MMSTOs and double RCs in such a picture. However, this brings a new challenge for the present dynamical formation model of stars and star clusters. Some works also studied the possibility of using observational selection (Keller et al. 2011) and uncertainty to interpret the observed CMDs but it seems to be unnatural (Goudfrooij et al. 2011b). The kind of model involving a mixture of stars with and without overshooting cannot fit the observed CMD either (Girardi et al. 2011). The latest model (Platais et al. 2012) showed the potential of differential reddening to explain the apparent splitting/widening of MSTOs of a Galactic open cluster, Trumpler 20, but an age spread is needed. Although most works give their explanation based on single stars, a few works argue that unresolved binary stars may result in extended MS and dual RC (Milone et al. 2009; Yang et al. 2011), but it cannot reproduce some peculiar CMD structures, e.g., the golf club shape (Mackey et al. 2008; Goudfrooij et al. 2009; Milone et al. 2009). Even so, the importance of stellar rotation and binaries in modeling CMDs is obvious (Hurley & Tout 1998; Goudfrooij et al. 2009; Bastian & de Mink 2009; Li et al. 2010; Girardi et al. 2011; Yang et al. 2011). Because it is well known that all star clusters possibly contain a large number of binaries (e.g., Abt 1979; Lada 2006) and massive rotating stars (e.g., Peterson et al. 2004; McAlister et al. 2005; Royer et al. 2007), it is necessary to study the CMDs of intermediate-age star clusters via a combination of the two natural factors in more detail. This is the aim of the present Letter. The difference between this work and previous ones (e.g., Girardi et al. 2011; Yang et al. 2011) is on the construction of stellar populations and the treatment of rotational effect. The
effect of stellar rotation is considered using the result of Bastian & de Mink (2009) and taking a different distribution for the rotation rate (\(\omega\)). The treatment of stellar rotation in Bastian & de Mink (2009) is actually different from Girardi et al. (2011), but it agrees with the results of the Geneva group (Bastian & de Mink 2009). Stars with different masses are considered in our model and a binary fraction similar to the one observed is used, which makes the theoretical population more similar to real star clusters than that in Yang et al. (2011). The results are found to be different from previous works.

The structure of this Letter is as follows. Section 2 introduces the construction of CMDs, Section 3 shows the main results. Finally, we summarize and discuss the work in Section 4.

2. CONSTRUCTION OF CMDs

We construct synthetic CMDs following our previous work (e.g., Li & Han 2008a, 2008b, 2008c; Li et al. 2010, 2012; Zhongmu 2011) on modeling binary star stellar population (bsSP) and single star stellar population (ssSP). In detail, the initial mass function (IMF) of Salpeter (1955) is adopted to generate our sample stars. In order to build up binaries, the mass of the primary component of a binary is generated first within the range of 0.1 to 100 \(M_\odot\). Note that unlike Yang et al. (2011), we do not exclude any stars, as the masses of two components in an interactive binary can transfer and change during evolution. Then the mass of the secondary component is calculated by taking a random secondary-to-primary mass ratio (\(q\)) (Han et al. 1995). \(q\) is assumed to obey a uniform distribution within 0–1. The separations (\(a\)) of two components is given under the assumption that \(a\) is constant in log \(a\) for wide binaries and falls off smoothly at close separation (Han et al. 1995), which can be expressed by

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

where \(\alpha_{\text{sep}} \approx 0.070, a_0 = 10 R_\odot, a_1 = 5.75 \times 10^6 R_\odot = 0.13\) pc, and \(m \approx 1.2\). This gives us a sample with about half binary stars with orbital periods less than 100 yr (Han et al. 1995) and half single stars. After that, a random eccentricity (\(e\)) within 0–1 is assigned to each binary, as \(e\) slightly affects the evolution of stars (Hurley et al. 2002). Because the binary fraction of real clusters is possibly lower than 50% (about 30%–40%, see e.g., Elson et al. 1998), we define our sample by removing some random binaries from the generated sample. It leads to a new sample with a binary fraction of 35%, which is then used in this work.

After the sample generation, all stars are evolved using the rapid stellar evolution code of Hurley et al. (2002; Hurley code), which uses some formulae fitted from the evolutionary tracks of stellar models to evolve stars and does not take stellar rotation into account. For stellar populations including rotational stars, we add the effect of rotation on effective temperature and luminosity to the parameters of massive (>1.2 \(M_\odot\)) stars that have not left main sequence (MS), using two fitted correlations presented by Bastian & de Mink (2009). This treatment follows the work of Bastian & de Mink (2009). However, we adopt a Gaussian distribution with a mean and standard deviation of 0.55 and 0.25 (or 0.15) for the rotation rate (\(\omega\)), according to the \(\omega\) distribution of some A and F type stars in Royer et al. (2007) and a similar application by Bastian & de Mink (2009). We also assume that \(\omega\) increases gradually with stellar mass, which gives the final \(\omega\) by multiplying a factor between 0 to 10 for each star (see also Bastian & de Mink 2009). The factor linearly increases with mass, and the values for 1.2 \(M_\odot\) and 1.5 \(M_\odot\) are zero and one, respectively. The effect of inclination is randomly set to about 0.2 times that caused by \(\omega\), according to the result of Bastian & de Mink (2009). A small blue shift of about 0.01 mag in the \((V - I)\) of fast rotators is also taken into account, according to the result of Platais et al. (2012). Some limitations in the treatment of stellar rotation will be discussed later. Finally, we transform the evolutionary parameters (\([Fe/H], T_{\text{eff}}, \log g, \log L\)) into colors and magnitudes using the atmosphere library of Lejeune et al. (1998).

3. RESULTS

Figure 1 shows the CMDs of a few binary star simple stellar populations (bsSSPs) and binary star composite stellar populations (bsCSPs) with \(Z = 0.008\). The CMDs in the six panels are generated by taking different assumptions, and the last four are similar to observed CMDs of intermediate-age star clusters in the LMC. Panel (a) shows the CMD of a bsSSP when all stars could be resolved. It aims to show the direct effect of binary evolution or interactions on the CMD. A binary fraction of 35% and star count of 76,922 are taken for this population. We see that binary interactions lead to some blue stragglers (BSs) and dual RCs. BSs are mainly caused by mass transfer, star merger, and possibly high runaway velocity of stars (see also Pols & Mar{\^i}nus 1994). The dual RC results from both normal stars (single and unmerged binary components), and merged (most) or interactive binaries. In addition, the turnoff is obviously dominated by single stars in the population. This implies that binary interaction slightly contributes to the observed turnoff spread. Note that the turnoff mass in the population is about 1.5 \(M_\odot\) and the deep sequence is close to the isochrone of an ssSP with the same metallicity and age. Furthermore, some red stragglers (or subgiants, hereafter RSs) are shown on the right of the MS and under the giant branch. They are the primary binary components which transferred mass to secondary ones. Some of the observed stars in clusters (e.g., NGC 1846) are possibly such stars.

Panel (b) shows a CMD taking into account the spatial resolution of HST ACS. The distance of the LMC is taken to be 160,000 lt-yr, and the angle between the line of sight and the connecting line of two binary components is given randomly. This results in about 85% unresolved binaries. We find that MS becomes wider and two parts (blue and red) are shown, in which the blue one is obviously dense and narrow. At the same time, double turnoffs (2 MSTOs) are presented, but their locations seem to be different from the CMDs of star clusters in the LMC. Comparing to panel (a), we see that the upper of the two MSTOs is caused by unresolved binaries. For convenience, we cite the effect of both binary evolution and resolution as a binary effect in this Letter. Note that the CMD does not have a golf club shape.

Next, in panel (c) we consider both the effects of binaries and stellar rotation in a population. When the effect of rotation is taken into account, the population shows a unique golf club shape similar to the observed CMDs of some LMC clusters. In detail, the bsSSP with rotational stars has an obvious spread in the main sequence and extended turnoff. It also shows dual RCs and BSs. As a test, we find that the number (about seven) of BSs in a fixed range, which is shown by blue lines and is slightly affected by a field star, is similar to that in NGC 1846 when considering only quality-filtered stars within 30" from the center (see Figure 3 of Mackey et al. 2008 for comparison).
Figure 1. Synthetic CMDs. “bsSSP” and “bsCSP” denote the binary star simple and composite stellar populations, respectively. The fraction of unresolved binaries is calculated from binary separations and the spatial resolution of HST ACS. $N_p$ is the number of star pairs in a population at zero age, which is similar for all panels. $N_{\text{obj}}$ is the number of objects or points in the shown ranges and for the given populations. The two ranges shown by blue lines include BSs that are compared to those of NGC 1846 (Mackey et al. 2008). Errors in $V$ and $V-I$ follow Gaussian distributions with standard deviations of 0.01 and 0.014 mag. “nonrotation + rotation” means half non-rotating stars and half rotational stars.

The distance modulus and color excess are taken as 18.45 and 0.1 mag, respectively, in comparison. The panel shows that single stars, separated binary components, and unresolved stars have some contributions to the shape of CMD.

When comparing the CMD with an isochrone (red points in panel (c)) of a single star simple stellar population (ssSSP) with the same metallicity and age as the bsSSP, we find that the ssSSP isochrone is located near the blue, dense MS part of bsSSP. It implies that stellar metallicity and age can possibly be estimated by fitting the dense MS using the isochrones of ssSSPs. Because the turnoff part lower than the ssSSP isochrone is mainly caused by stellar rotation, it does not indicate additional populations. However, as shown by Girardi et al. (2011), it can be explained by prolonged star formation history.
In panel (d), we show the CMD for the same population, but with a narrow distribution of the rotation rate for some stars. In this test, half of the stars are assumed to rotate with a Gaussian distribution for \( \omega \), which peaks at 0.55, and with a standard deviation of 0.15. We use this assumption because some works show bimodal \( \omega \) distributions that peak near 0.1 and 0.5–0.6 for some A and F type stars (e.g., Royer et al. 2007). Our treatment gives similar results, with two peaks of 0.1 and 0.55 for \( \omega \). This model reproduces the CMD with double turnoffs. Similar CMDs have been observed in some star clusters. Because some other works used two ssSSPs to explain similar CMDs, we plot the isochrones of two ssSSPs with ages of 1.4 and 1.7 Gyr in this figure as a comparison. We can see that the rotation effect can also be interpreted as one more stellar population.

By comparing the CMDs in panels (c) and (d) to those of star clusters, we find that they can fit to the observed CMDs of most intermediate-age star clusters. Besides the extended MS or MMSTOs, bsSPs with rotation effects can fit the BSs, dual RCs, and some RSs (e.g., NGC 1846 and NGC 1987; see, e.g., Milone et al. 2009) naturally. Note that RSs can be reproduced by assuming more complete and resolved binaries. Therefore, it is possible that many star clusters are actually bsSSPs with stellar rotation. This supports to the classical picture of stellar population of star clusters, i.e., the SSP scenario.

As some works argued that prolonged star formation history may be the best choice for interpreting the CMDs of star clusters (e.g., Girardi et al. 2011), it is necessary to compare the CMD of bsSSP to that of composite stellar populations (CSPs). We do this in panels (e) and (f). Panel (e) shows a CMD of a bsCSP with the same metallicity as the bsSSP in panel (c). The stars in the bsCSP are assumed to form within 300 Myr from 1.5 Gyr by four starbursts. We see that this case reproduces wider MSTO and RC. It also has a golf club shape. Similarly, panel (f) shows a bsCSP with two subpopulations, and, considering the effect of a narrow \( \omega \) distribution, we find that more MSTOs are generated. This suggests that the picture of continuous star formation history is not the only one that can explain MMSTOs (see Girardi et al. 2011 for comparison). A simple model with two starbursts or a merger of two clusters can potentially explain most CMDs with MMSTOs.

4. CONCLUSION AND DISCUSSION

This Letter uses the combined effects of binaries and stellar rotation to interpret the CMDs of intermediate-age star clusters in LMC. It is shown that most observed CMD features can be reproduced via both bsSSP or bsCSP with two subpopulations. In detail, the model can show MMSTOs, broad main sequences with two parts, dual RCs, and blue and red stragglers. It suggests that the MS spread and MMSTOs possibly result from both rotation and binary effects, while dual RCs, blue and red stragglers are mainly caused by binary interactions (merger and mass transfer). In addition, the combined effects of binaries and stellar rotation leads to CMDs with a golf club shape turnoff, which is similar to the observed result. Furthermore, bsSPs are shown to have some intrinsic spread in MS, which results from unresolved binaries. By taking different assumptions for the stellar rotation rate, both extended or double MSTOs can be reproduced from a bsSSP. Therefore, the special CMD shapes of many intermediate-age star clusters in the LMC can be explained by including both stellar rotation and binary effects in the SSP models. In this case, many star clusters with special CMDs are possibly SSPs, rather than CSPs. Even if CSPs are needed, some models with two components can potentially explain the observed CMDs.

Although the simple model considering both binary effect and stellar rotation seems to be successful in reproducing the shape of CMDs of intermediate-age star clusters, it is far from being able to understand well the observed CMDs. First, there are many uncertainties in the model. The density of blue and red MS parts and the number of blue and red stragglers directly relate to the number of total and unresolved binaries. Besides, while the treatment of rotation is derived from detailed stellar evolutionary models, the effects of rotation on stellar interiors and their appearance is considerably uncertain. It should be noted that these models are one-dimensional models in which rotation is treated in a simple diffusive approximation. On the more massive end of the spectra, serious questions have been raised about the effects of rotation on interior mixing (Hunter et al. 2011; Brott et al. 2011). Second, the difference between the results of this work and Girardi et al. (2011) mainly results from different treatments of the stellar rotation, because different assumptions (single or distributed) for rotation rate can lead to quite different CMD features. Although it is reasonable to take a Gaussian distribution for a rotation rate following the observational result, and assume that massive stars rotate faster since lower mass stars have convective envelopes, which may generate magnetic fields through dynamos spinning the stars down, our treatment is actually simplistic and artificial. This needs to be done better in future studies using either an empirical mass dependence, a grid, or detailed models accounting for rotation and a certain magnetic braking prescription. In addition, two simple fitting formulae were used to model the effect of stellar rotation, so the effect of rotation on stars’ lifetime, which is mainly responsible for different color shifts caused by rotation in this work and in Girardi et al. (2011), and the relation between binarity and rotation have not been taken into account. The use of a stellar evolutionary code including both binarity and rotation would be beneficial in future works. Furthermore, the effects of binary interaction and rotation are implemented as two independent effects. In fact, in many cases binarity may be the cause of rapid rotation. Moreover, this work did not consider the dynamical and chemical evolution of star clusters. They may supply important clues for better understanding some gradients for building CMDs, especially star formation history. Finally, many factors may affect the observed CMDs, and their roles (e.g., prolonged star formation and rotation) are somewhat degenerate. This can only be disentangled by a series of works involving improvement in both observation and theoretical modeling.

We thank the referee for constructive comments and Eva K. Grebel for suggestions. This work has been supported by the Chinese National Science Foundation (grant Nos. 10963001 and 11203005), Yunnan Science Foundation (No. 2009CD093), and Chinese Postdoctoral Science Foundation. Z.L. gratefully acknowledges the support of Sino-German Center (GZ585) and K. C. Wong Education Foundation, Hong Kong.

REFERENCES

Abt, H. A. 1979, AJ, 84, 1591
Bastian, N., & de Mink, S. E. 2009, MNRAS, 398, L11
Bertelli, G., Nasi, E., Girardi, L., et al. 2003, AJ, 125, 770
Brott, I., Evans, C. J., Hunter, I., et al. 2011, A&A, 530, A116
D’Ecreole, A., Vesperini, E., D’Antona, F., McMillan, S. L. W., & Recchi, S. 2008, MNRAS, 391, 825
Li, Z.-M., Mao, C.-Y., Li, R.-H., Li, R.-X., & Li, M.-C. 2010, Res. Astron. Astrophys., 10, 135
Mackey, A. D., & Broby Nielsen, P. 2007, MNRAS, 379, 151
Mackey, A. D., Broby Nielsen, P., Ferguson, A. M. N., & Richardson, J. C. 2008, ApJ, 681, L17
McAlister, H. A., ten Brummelaar, T. A., Gies, D. R., et al. 2005, ApJ, 628, 439
Milone, A. P., Bedin, L. R., Piotto, G., & Anderson, J. 2009, A&A, 497, 755
Milone, A. P., Piotto, G., King, I. R., et al. 2010, ApJ, 709, 1183
Mucciarelli, A., Carretta, E., Origlia, L., & Ferraro, F. R. 2008, AJ, 136, 375
Peterson, D. M., Hummel, C. A., Pauls, T. A., et al. 2004, Proc. SPIE, 5491, 65
Piotto, G., Bedin, L. R., Anderson, J., et al. 2007, ApJ, 661, L53
Piotto, G., Villanova, S., Bedin, L. R., et al. 2005, ApJ, 621, 777
Platais, I., Melo, C., Quinn, S. N., et al. 2012, ApJ, 751, L8
Pols, O. R., & Marinus, M. 1994, A&A, 288, 475
Royer, F., Zorec, J., & Gómez, A. E. 2007, A&A, 463, 671
Rubele, S., Girardi, L., Kozhurina-Platais, V., & Kerber, L. 2011, MNRAS, 414, 2204
Rubele, S., & Girardi, L. 2010, MNRAS, 403, 1156
Salpeter, E. E. 1955, ApJ, 121, 161
Yang, W., Meng, X., Bi, S., et al. 2011, ApJ, 731, L37
Zhongmu, L. 2011, in ASP Conf. Ser. 451, 9th Pacific Rim Conference on Stellar Astrophysics, ed. S. Qain, K. Leung, L. Zhu, & S. Kwok (San Francisco, CA: ASP), 51