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A binary study of color-magnitude diagrams of 12 globular clusters *

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Abstract Binary stars are common in star clusters and galaxies, but the detailed effects of binary evolution are not taken into account in some color-magnitude diagram (CMD) studies. This paper studies the CMDs of twelve globular clusters via binary-star stellar populations. The observational CMDs of the star clusters are compared to those of binary-star populations, and then the stellar metallicities, ages, distances and reddenings of these star clusters are obtained. The paper also tests the different effects of binary and single stars on CMD studies. It is shown that binaries can better fit the observational CMDs of the sample globular clusters compared to single stars. This suggests that the effects of binary evolution should be considered when modeling the CMDs and stellar populations of star clusters and galaxies.

Key words: (Galaxy:) globular clusters: general — galaxies: star clusters

1 INTRODUCTION

Star clusters are important objects in astrophysical studies. Their associated color-magnitude diagrams (CMDs) are usually used to determine the properties of star clusters, i.e., stellar ages, metallicities, distances, and reddenings (see, e.g., Naylor & Jeffries 2006; Kalirai & Tosi 2004). In most studies, the theoretical isochrones of some single-star simple stellar populations (ssSSPs) (e.g., Momany et al. 2003) are used, because their corresponding CMDs are shown as simple curves and are convenient for these kinds of studies. Meanwhile, some researchers use observed template CMDs (Recio-Blanco et al. 2005) for similar studies. Recently, some have studied the CMDs of star clusters via more advanced techniques, i.e., Monte Carlo simulations. One can refer to the papers, e.g., Kalirai & Tosi (2004), Aparicio et al. (1990), Tosi et al. (1991), Hurley & Tout (1998), and Skillman & Gallart (2002), for more information. Such methods are more advanced and can give additional parameters such as binary fractions and star formation histories to star clusters. This represents important progress because these methods take binary effects into account. Although the new methods are much more informative and rewarding, they usually need more constraints on the properties of star clusters from independent techniques to make the fittings tractable, and such methods are used to study some star clusters with accurately observed CMDs. Therefore, it is difficult to study the CMDs of a big sample of star clusters because of the limitation in accuracy of observed

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CMDs and known properties of star clusters. In addition, most studies focus on the widening of the main sequences of theoretical CMDs when considering the binary effects in the comparisons of observational and theoretical CMDs (e.g., Naylor & Jeffries 2006). However, according to Kalirai & Tosi (2004) and Li & Han (2008), binary evolution affects not only the shapes of some particular parts of CMDs, but also the number distributions of stars in CMDs. Therefore, it is necessary to take the detailed effects of binary evolution into account in CMD studies.

According to the studies of Li & Han (2008) and Li & Han (2009), binary evolution can affect the integrated features of populations. Besides the widening of isochrones, binary evolution can explain some special stars such as blue stragglers in star clusters. It can also interpret the UV excess in elliptical galaxies (see, e.g., Han et al. 2007). Therefore, it is proposed to use CMD studies on the basis of some stellar populations that have taken the detailed effects of binary evolution into account. If the effects of binary evolution are taken into account, some different properties of star clusters may be obtained. This is helpful for the further understanding of star clusters. In addition, because a stellar isochrone is a basic ingredient to build stellar populations, comparing the CMDs of star clusters with the synthetic CMDs of binaries can help us to model stellar populations in more advanced ways. This paper aims to study the CMDs of a few star clusters via binary stars, and then compare the results determined by binary- and single-star simple stellar populations (bsSSPs and ssSSPs). Because globular clusters (GCs) are usually thought to be simple systems that include metal-poor and old stars, we take some GCs as the star cluster sample of this study.

The paper is organized as follows. In Section 2, we introduce our sample GCs and their observational CMDs. In Section 3, we summarize the features of the theoretical CMDs of stellar populations. In Section 4, we present the binary fittings of the CMDs of star clusters and show the properties of the GCs. In Section 5, we compare the results determined respectively by binary- and single-star populations. Finally, in Sections 6 and 7, we give our discussion and conclusions.

2 SAMPLE GLOBULAR CLUSTERS AND THEIR PHOTOMETRY

There are a lot of observational results for the CMDs of globular clusters and some have been presented recently (e.g., Piotto et al. 2002; Kerber & Santiago 2005). We take observational results from a catalog of the UBV HR diagrams of globular clusters (Philip et al. 2006, hereafter called the Philip catalog) for this work. The reason is that these observational data show some clear CMDs and seem reliable. In addition, photometry results have less uncertainties than spectral results, and the photometry source slightly affects the final results. Furthermore, we aim at using binaries as a way to study the CMDs rather than to obtain accurate properties of star clusters. Thus, the selected CMDs are suitable for this work. The Philip catalog has 65 color-magnitude diagrams of star clusters, which are compiled from the literature. Some star clusters in the catalog are shown with a few CMDs derived from different sources. When choosing the CMDs used in the work, the ones with better CMD shapes are taken. As a result, we choose twelve globular clusters from the catalog. The twelve globular clusters are NGC 104, NGC 2419, NGC 4147, NGC 4372, NGC 5272, NGC 5897, M5, NGC 6205, M10, NGC 6352, NGC 6397, and NGC 6809. Note that all the sample clusters contain more than 100 observed stars. This possibly makes the results more reliable.

3 THEORETICAL COLOR-MAGNITUDE DIAGRAMS

Theoretical CMDs are basic ingredients of this work. This work uses two types of theoretical CMDs, i.e., the CMDs of bsSSPs and ssSSPs. Both types of theoretical CMDs are built on the basis of an isochrone database of stellar population studies (Li & Han 2008). For convenience, we take a Salpeter shape (Salpeter 1955) for the initial mass function of theoretical stellar populations. When modeling binary-star stellar populations, a fraction of 50% is taken for the binaries that have orbital periods less than 100 yr (the typical value of the Milky Way), and the lower and upper mass limits are set to be 0.1 and 100 solar masses, respectively. The stellar evolution is calculated by a rapid star evolution code of Hurley et al. (2002) (hereafter Hurley code). In each bsSSP, binary interaction, such as mass transfer, mass accretion, common-envelope evolution, collisions, supernova kicks, angular momentum loss mechanism, and tidal interactions, are considered. Some default parameters of the Hurley code, i.e., 0.5, 1.5, 1.0, 0.0, 0.001, 3.0, 190.0, 0.5, and 0.5, are taken for the wind velocity factor ($\beta_{\rm w}$), Bondi-Hoyle wind accretion faction ($\alpha_{\rm w}$), wind accretion efficiency factor ($\mu_{\rm w}$), binary enhanced mass loss parameter ($B_{\rm w}$), fraction of accreted material retained in supernova explosions (ϵ), common-envelope efficiency ($\alpha_{\rm CE}$), dispersion in the Maxwellian distribution for the supernova kick speed ($\sigma_{\rm k}$), Reimers coefficient for mass loss (η), and binding energy factor (λ), respectively. These values are taken because they have been tested by Hurley et al. (2002) and seem more reliable than other ones. One can refer to the paper of Hurley et al. (2002) for more details. Therefore, many of these free parameters retain large uncertainties, and they need to be studied in more detail in the future. Accordingly, this work is limited by the isochrone database, although it is a convenient choice. In addition, the BaSeL 2.2 photometry library (Lejeune 1998) is used when transforming the isochrone database into the CMDs of bsSSPs and ssSSPs.

4 BINARY FITTING OF COLOR-MAGNITUDE DIAGRAMS OF GLOBULAR CLUSTERS

Based on the theoretical CMDs of bsSSPs, we fit the CMDs of our sample clusters and derive some basic parameters of these clusters in this section. In order to get reliable results, big ranges are used for the stellar ages and metallicities of theoretical populations when fitting the observational CMDs of star clusters. In detail, the stellar age and metallicity ranges are taken as 0.1 – 15 Gyr and 0.0001 – 0.03, respectively. These are just the default ranges of the isochrone database used by this work. Although the largest metallicity of the theoretical populations is only 0.03, it is enough for studying the CMDs of most globular clusters, as globular clusters are usually metal-poor ($Z \leq 0.03$). Because the observational data of stars with high luminosities have less observational uncertainties, a magnitude-weighted method is taken in this work. This can possibly enhance the reliability of the fitting results. To be clear, we compare the observational and best-fit theoretical CMDs of 12 GCs in Figures 1, 2 and 3. The best-fit CMDs are found by comparing the distribution of stars in theoretical CMDs to that in observational CMDs. The advantage of such a method is that both the shape and luminosity function are compared at the same time.

As shown in Figures 1, 2, and 3, we can see that the main shapes of the CMDs of star clusters are reproduced well. Therefore, the properties of star clusters derived from the CMD fitting are reliable. In detail, the stellar ages, metallicities, distances, and reddenings determined by comparing observational CMDs to synthetic CMDs are listed in Table 1. It shows that these clusters have a minimum age of 4 Gyr and a maximum age of 13 Gyr, with an average of 11.42 Gyr. The lowest and highest metallicities (Z) of these globular clusters are 0.0001 and 0.01, respectively, with an average of 0.00145. As a whole, the results show old ages and poor metallicities for globular clusters. This is in agreement with most previous studies.

5 COMPARISON OF DIFFERENT RESULTS

Some bsSSP models are used for studying the CMDs of globular clusters in this work, but most other studies use ssSSP models. In order to investigate the differences between the CMD study results derived from bsSSP and ssSSP models, we compare the observational CMDs of two globular clusters (M5 and NGC 6397) with those of theoretical bsSSPs and ssSSPs. The two clusters are chosen for the study because their CMDs are intact. In Figure 4, the detailed comparison of the observational CMDs with the best-fit theoretical CMDs of bsSSPs and ssSSPs is shown. We see that the CMDs of best-fit bsSSPs cover larger ranges in the color versus magnitude field compared to the best-fit ssSSPs, and the CMDs of bsSSPs are actually closer to the observational CMDs of the two globular clusters. When comparing the properties determined by bsSSPs and ssSSPs, they are

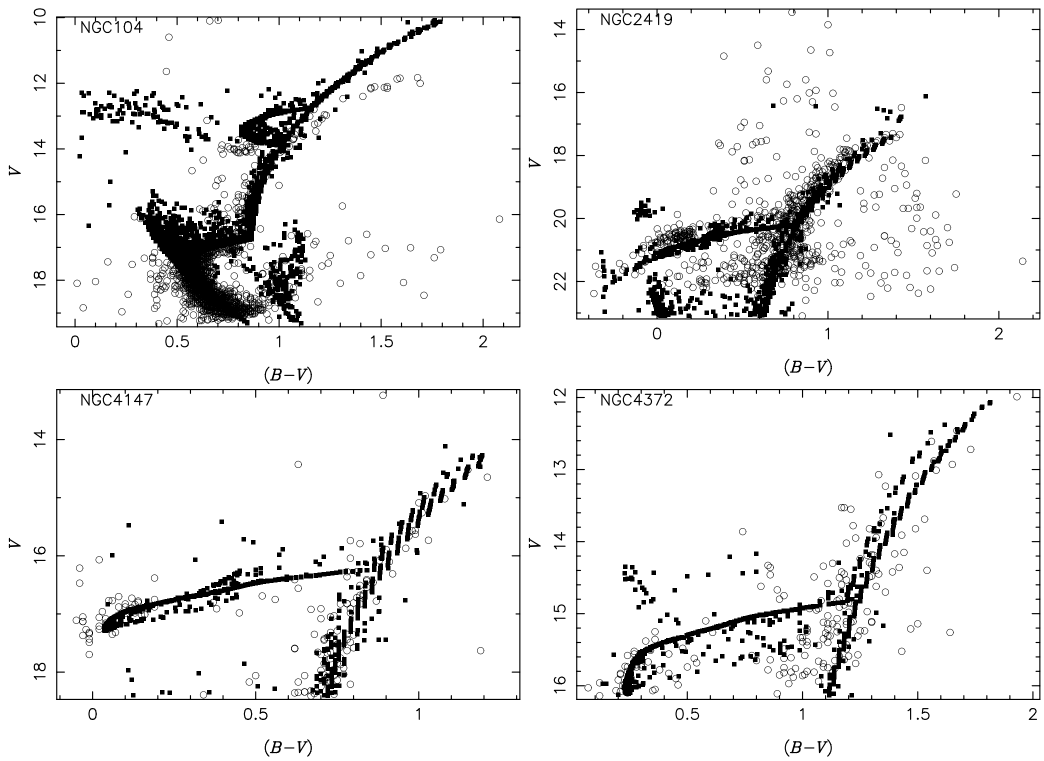

Fig. 1 Comparison of observational (*circles*) and best fit theoretical (*squares*) CMDs, for globular clusters NGC 104, NGC 2419, NGC 4147, and NGC 4372, respectively. The theoretical CMDs are calculated from binary-star populations with 50% binaries and each star is assumed to be discriminable. In the field shown in the figure, the observational and theoretical CMDs contain the same stars, but a few red points contain less than 1 star.

Table 1 Best fit properties (stellar age, metallicity, distance modulus, and reddening) of 12 globular clusters. The best fit results are obtained by comparing the observed CMDs to the CMDs of binary-star stellar populations. Note that a magnitude-weighted method is used in the fitting.

Cluster Name	Age [Gyr]	Metallicity (Z)	$(m-M)_V$ [mag]	$E(B-V)$ [mag]
NGC 104	11.3	0.0040	13.4	0.10
NGC 2419	9.7	0.0001	20.8	0.00
NGC 4147	10.6	0.0001	16.8	0.06
NGC 4372	14.3	0.0010	15.4	0.30
NGC 5272	12.5	0.0001	15.4	0.16
NGC 5897	11.9	0.0001	16.4	0.16
M5	9.5	0.0003	14.8	0.12
NGC 6205	12.4	0.0003	14.8	0.04
M10	11.6	0.0010	15.2	0.20
NGC 6352	8.4	0.0100	15.6	0.24
NGC 6397	11.4	0.0001	13.2	0.10
NGC 6809	13.4	0.0003	14.2	0.12

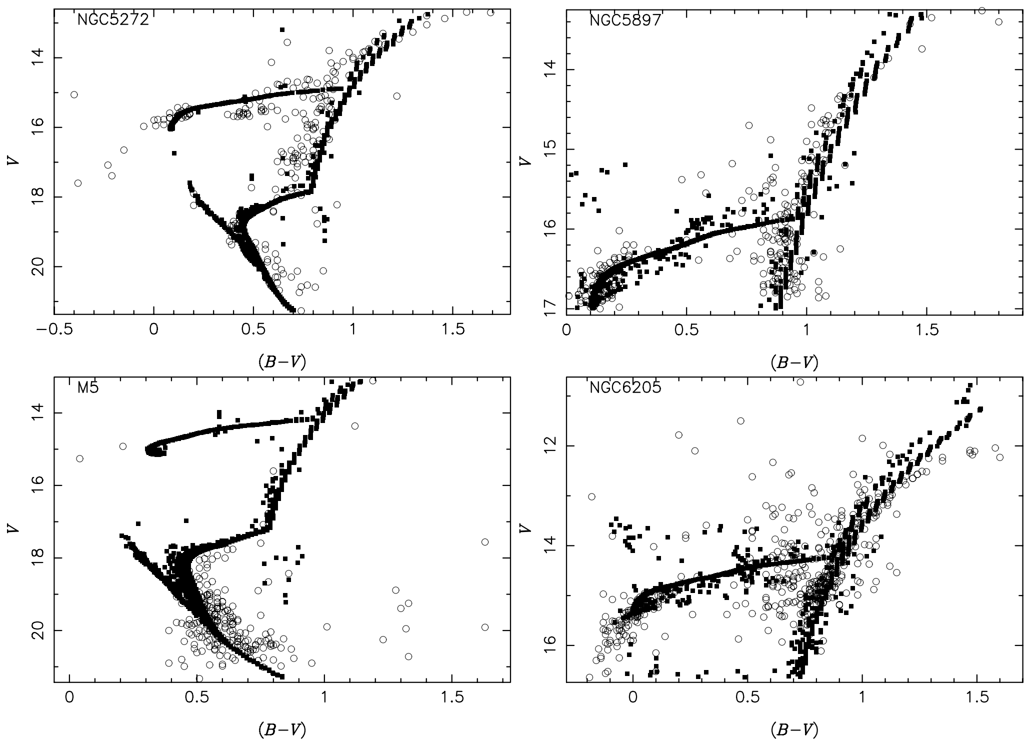

Fig. 2 Similar to Fig. 1, but for NGC 5272, NGC 5897, M5, and NGC 6205.

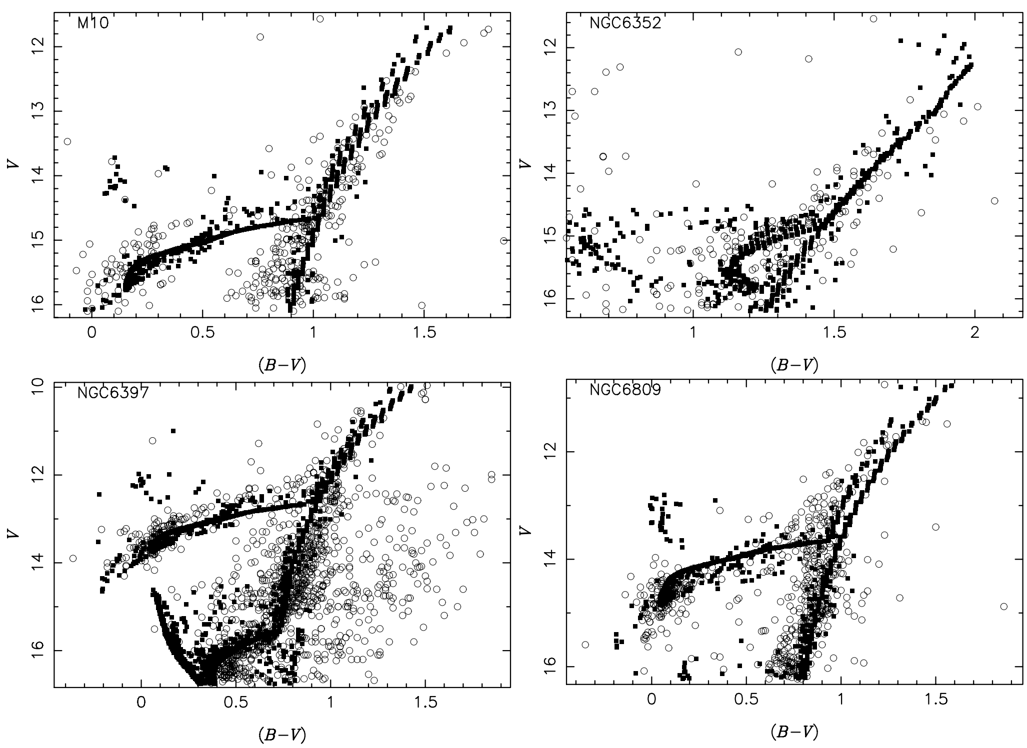

Fig. 3 Similar to Fig. 1, but for M10, NGC 6352, NGC 6397, and NGC 6809.

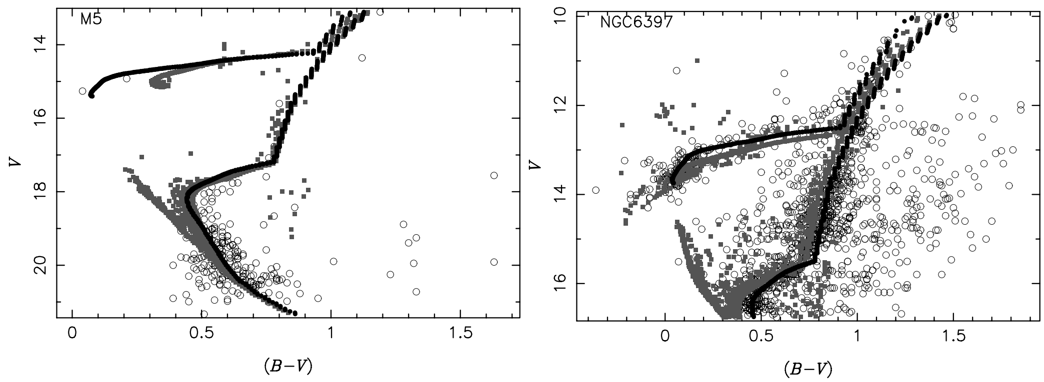

Fig. 4 Comparison of the observational CMDs (*circles*) of star clusters M5 and NGC 6397 to the best fit bsSSP (*gray squares*) and ssSSP (*black points*) theoretical CMDs. A bsSSP takes 50% of the stars to be binaries for its population of stars and an ssSSP assumes that the whole population of stars are single stars.

shown to be different. In detail, the best bsSSP fit results of age, metallicity, distance modulus in the V band, and reddening $E(B-V)$ of M5 are 9.5 Gyr, 0.0003, 14.8 mag, and 0.12 mag respectively, while the ssSSP fit results are 12.6 Gyr, 0.0001, 14.75 mag, and 0.15 mag, respectively. The other star cluster, NGC 6397, shows bsSSP fit properties of 11.4 Gyr (age), 0.0001 (metallicity Z), 13.2 mag (distance modulus), 0.1 mag (reddening), as well as ssSSP results of 13.6 Gyr, 0.0001, 13.0 mag, and 0.15 mag, respectively. Because the same method was used for the bsSSP and ssSSP fittings, the differences result from the stellar population models.

6 DISCUSSION

Binary stars can explain the observational CMDs of globular clusters as a whole, but it is clear that there are some differences between the observational and theoretical CMDs. This possibly results from the following reasons: Firstly, there are some limitations in our theoretical stellar populations. For example, the basic inputs (e.g., binary fraction, initial mass function, etc.) of the bsSSP model remain uncertain and the metallicity intervals are not small enough. Note that the binary fractions in GCs are possibly lower than those ($\sim$ 50%) in the local fields, open clusters, and star-forming regions, because frequent dynamical interactions together with binary evolution processes conspire to effectively destroy binaries in GCs. Secondly, it seems impossible to discriminate every star in the star clusters, but each star is assumed to be distinguishable in our work because there is no reliable instruction about how stars in a cluster can be distinguished. This effect is obvious in the low luminosity part of the main sequences of CMDs. Thirdly, it seems that there are some uncertainties in the observational CMDs. In addition, the effect of superposition in CMDs has not been taken into account in this work, thus, this also can considerably affect morphology, especially in crowded regions such as cluster centers.

7 CONCLUSIONS

This paper presents a binary-star study for the color-magnitude diagrams of 12 globular clusters, in which each star is assumed to be distinguishable. It shows that the CMDs of star clusters can be explained well via binary-star populations, although some differences are shown when comparing observational and theoretical CMDs. As a result of the study, some basic properties, i.e., stellar age, metallicity, distance modulus, and color excess, are determined for the 12 sample clusters. The sample clusters are shown to be old (Age ≥ 8.4 Gyr) and metal poor ($Z \leq 0.01$). When we compare the cluster properties determined by binary- and single-star stellar populations, respectively, it shows that the two types of population models can give different results for star clusters. Because binary stars are common, the study suggests using a binary method to study the CMDs of star clusters. It also suggests modeling the stellar populations of star clusters via binary stars.

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