HOW BINARY INTERACTIONS AFFECT SPECTRAL STELLAR POPULATION SYNTHESIS

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ABSTRACT

Single-star stellar population (ssSSP) models are usually used for spectral stellar population studies. However, more than 50% of stars are in binaries and evolve differently from single stars. This suggests that the effects of binary interactions should be considered when modeling the stellar populations of galaxies and star clusters. Via a rapid spectral stellar population synthesis model, we give detailed studies of the effects of binary interactions on the Lick indices and colors of stellar populations and on the determination of the stellar ages and metallicities of populations. Our results show that binary interactions make stellar populations less luminous and bluer, with larger age-sensitive Lick indices (Hβ) and smaller metallicity-sensitive indices (e.g., Mg b, Fe5270, and Fe5335) compared to ssSSPs. It also shows that when ssSSP models are used to determine the ages and metallicities of stellar populations, smaller ages or metallicities are obtained when using two line indices (Hβ and [MgFe]) or two colors (e.g., u − R and R − K), respectively. Some relations for linking the stellar population parameters obtained by ssSSPs to those obtained by binary-star stellar populations (bsSSPs) are presented in this work. This can help us get some absolute values for stellar population parameters and is useful for absolute studies. However, it is found that the relative luminosity-weighted stellar ages and metallicities obtained via ssSSPs and bsSSPs are similar. This suggests that ssSSPs can be used for most spectral stellar population studies, except in some special cases.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: stellar content

1. INTRODUCTION

Stellar population synthesis is a powerful technique for studying the stellar contents of galaxies and star clusters (see, e.g., Yongelson & Tutukov 1997; Tout et al. 1997; Pols et al. 1998; Hurley et al. 2007). It is also an important method for studying the formation and evolution of galaxies. Simple stellar population (SSP) models that do not take binary interactions into account are usually used for spectral stellar population studies, as most models are single-star stellar population (ssSSP) models (e.g., Bruzual & Charlot 2003; Vazdekis 1999; Fioe & Rocca-Volmerange 1997; Worthey 1994). However, as noted by, e.g., Duquennoy & Mayor (1991), Pinfield et al. (2003), and Lodieu et al. (2007), about 50% of stars are in binaries, and they evolve differently from single stars. We can see this when comparing the isochrone of an ssSSP to that of a binary-star stellar population (bsSSP; Fig. 1). In fact, bsSSPs better fit the color-magnitude diagrams (CMDs) of star clusters than ssSSPs (Li & Han 2008b). This suggests that binary interactions can affect stellar population synthesis studies significantly, and it is, therefore, necessary to consider binary interactions. This is also supported by some observational results, e.g., the far-UV excess of elliptical galaxies (Han et al. 2007) and blue stragglers in star clusters (e.g., Davies et al. 2004; Tian et al. 2006; Xin et al. 2007). These phenomena can be naturally explained via stellar populations with binary interactions, without any special assumptions.

A few works have tried to model populations via binary stars and have presented some results on the effects of binary interactions on spectral stellar population synthesis. For example, Zhang et al. (2004, 2005) showed that binary interactions can make bsSSPs bluer than ssSSPs. However, there is not a more detailed investigation about how binary interactions affect the Lick indices and colors of stellar populations or on the determination of stellar ages and metallicities. One of our previous works, Li & Han (2008b), compared bsSSPs to ssSSPs, but various stellar population models were used. This makes it difficult to understand the effects of the changes of Lick indices and colors of populations that result only from binary interactions. Furthermore, it did not show how binary interactions affect the determinations of stellar ages and metallicities. In this case, we have no clear picture for the differences between the predictions of bsSSPs and ssSSPs and do not well know the differences between luminosity-weighted stellar population parameters (age and metallicity) determined by bsSSPs and ssSSPs. Because all galaxies contain some binaries, detailed studies of the effects of binary interactions on the Lick indices and colors of populations are important, as are the determinations of stellar population parameters. In this work, we perform a detailed study of the effects of binary interactions on spectral stellar population synthesis studies via the rapid spectral population synthesis (RPS) model of Li & Han (2008b).

The paper is organized as follows. In § 2 we briefly introduce the RPS model. In § 3 we study the effects of binary interactions on the isochrones, spectral energy distributions (SEDs), Lick Observatory Image Dissector Scanner absorption-line indices (Lick indices), and colors of stellar populations. In § 4 we investigate the differences between stellar ages and metallicities fitted by ssSSPs and bsSSPs. Finally, in § 5 we give our discussion and conclusions.

2. THE RAPID SPECTRAL POPULATION SYNTHESIS MODEL

We use the results of the RPS model of Li & Han (2008b) for this work, as there is no other available model. The RPS model calculated the evolution of binaries and single stars via the rapid stellar evolution code of Hurley et al. (2002, hereafter the Hurley code) and used the spectral libraries of Martins et al. (2005) and...
Westera et al. (2002; BaSeL 3.1) for spectral synthesis. The model calculated the high-resolution (0.3 Å) SEDs, Lick indices, and colors for both bsSSPs and ssSSPs with the initial mass functions (IMFs) of Salpeter (1955) and Chabrier (2003). Note that the RPS model used a statistical isochrone database for modeling stellar populations (Li & Han 2008b). Each bsSSP contains about 50% stars that are in binaries with orbital periods less than 100 yr (the typical value of the Galaxy), and binary interactions such as mass transfer, mass accretion, common-envelope evolution, collisions, supernova kicks, angular momentum loss mechanism, and tidal interactions are considered when evolving binaries via the Hurley code. Thus, the RPS model is suitable for studying the effects of binary interactions on stellar population synthesis studies. However, some parameters, such as those used for describing the common-envelope prescription, mass-loss rates, and supernova kicks, are free parameters, and the default values in 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 used in this work for the wind velocity factor ($\beta_v$), Bondi-Hoyle wind accretion fraction ($\alpha_{\text{w}}$), wind accretion efficiency factor ($\mu_{\text{w}}$), binary-enhanced mass-loss parameter ($B_{\alpha}$), fraction of accreted material retained in supernova eruption ($\epsilon$), common-envelope efficiency ($\alpha_{\text{CE}}$), dispersion in the Maxwellian distribution for the supernova kick speed ($\sigma_k$), Reimers coefficient for mass loss ($\eta$), and binding energy factor ($\lambda$), respectively. These default values are used because they have been tested by the developer of the Hurley code and seem more reliable. One can refer to Hurley et al. (2002) for more details. In fact, many of these free parameters remain uncertain, and their uncertainties can possibly have great effects on our results. When we test the uncertainties caused by various $\alpha_{\text{CE}}$ and $\lambda$, we find that the number of blue stragglers can be changed as much as 40% compared to the default case. However, it is extremely difficult to give detailed uncertainties in spectral stellar population synthesis due to the free parameters, as we lack constraints on these free parameters (see Hurley et al. 2002). Therefore, when we estimate the synthetic uncertainties in our RPS model, the uncertainties due to variation of free parameters are not taken into account.

Because the fitted formulae used by the Hurley code to evolve stars lead to uncertainties less than about 5% (Hurley et al. 2002), we take 5% as the uncertainty in the evolution of stars in the whole paper. The correctness of the results of the RPS model depends on how correct the default parameters of the Hurley code are. In addition, the uncertainties in the final generated spectrum caused by the spectral library and the method used for spectral synthesis are about 3% and 0.81%, respectively. Because a Monte Carlo technique is used by the RPS model to generate the star sample (2 billion binaries, or 4 billion single stars, in our work is twice that of the model of Zhang et al. 2004) of stellar populations, the number of stars can result in statistical errors in the Lick indices and colors of populations. According to our test, 1 billion binaries are enough to get reliable Lick indices (see also Zhang et al. 2005), but the near-infrared colors such as $I - K$, $R - K$, and $r - K$ of old populations are affected by the Monte Carlo method. However, the errors caused by the Monte Carlo method are small, about 2% for a sample of 4 million stars. Note that in this work a uniform distribution is used to generate the ratio ($q$, 0–1) of the mass of the secondary to that of the primary (Mazeh et al. 1992; Goldberg & Mazeh 1994), and then the mass of the secondary is calculated from that of the primary and $q$. The separation ($a$) of the two components of a binary is generated following the assumption that the fraction of the binary in an interval of $\log a$ is constant when $a$ is big ($10 R_\odot < a < 5.75 \times 10^6 R_\odot$), and it falls off smoothly when $a$ is small ($\leq 10 R_\odot$; Han et al. 1995). The distribution of $a$ is written as

$$a \times p(a) = \begin{cases} a_{\text{sep}}(a/a_0)_\alpha^2, & a \leq a_0, \\ a_{\text{sep}}, & a_0 < a < a_1, \end{cases}$$

where $a_{\text{sep}} \approx 0.070$, $a_0 = 10 R_\odot$, $a_1 = 5.75 \times 10^6 R_\odot$, and $\psi \approx 1.2$. The eccentricity ($e$) of each binary system uses a uniform distribution in the range of 0–1, and $e$ affects the results slightly (Hurley et al. 2002).

In addition, the RPS model uses some methods that are different from those used in the work of Zhang et al. (2004) to calculate the SEDs, Lick indices, and colors of populations. RPS used a statistical isochrone database, and it calculated the Lick indices directly from SEDs, while the work of Zhang et al. (2004) used some fitting formulae to compute the same indices. The RPS model calculated the colors of populations from SEDs, but the work of Zhang et al. (2004) computed colors by interpolating the photometry library of BaSeL 2.2 (Lejeune et al. 1998). Furthermore, the RPS model used the more advanced version 3.1 (Westera et al. 2002) of the BaSeL library rather than version 2.2 to give the colors of the populations. The BaSeL 3.1 library overcomes the weakness of the BaSeL 2.2 library at low metallicity because it has been color-calibrated independently at all levels of metallicity. This makes the predictions of our model more reliable. Another important point is that the model of Zhang et al. did not present the near-infrared colors of stellar populations, but such colors are very important for disentangling the well-known age-metallicity degeneracy.

3. EFFECTS OF BINARY INTERACTIONS ON STELLAR POPULATION SYNTHESIS

3.1. The Effects on Isochrones of Stellar Populations

The direct effect of binary interactions on stellar population synthesis is to change the isochrones of stellar populations, e.g., the distribution of stars in the surface gravity ($\log g$) versus effective temperature ($T_{\text{eff}}$) grid (the $gT$ grid). We investigate the differences between the isochrones of bsSSPs and ssSSPs. Stellar populations with the IMF of Salpeter (1955) are taken as our standard models for this work. The Salpeter IMF is actually not the best one for stellar population studies, although it is widely used. The reason is that the IMF is not valid for low
masses. However, this IMF is reliable for stellar population synthesis because low-mass stars contribute much less to the light of populations compared to high-mass stars. Thus, some more reliable IMFs, e.g., Kroupa et al. (1993) can also be used for such studies. Because the isochrone database used by this work divides the $gT$ grid into 1,089,701 subgrids with intervals of log $g$ and $T_{\text{eff}}$ of 0.01 and 40 K, it is possible to compare the isochrones of bsSSPs and ssSSPs. The differences between the isochrones of the two kinds of populations are calculated by subtracting the fraction of stars of a bsSSP from that of its corresponding ssSSP, subgrid by subgrid. The ssSSP and its corresponding bsSSP have the same star sample, metallicity, and age, and all their integrated specialties (SEDs, colors, and Lick indices) are calculated via the same method. Therefore, the differences between the isochrones of a bsSSP and its corresponding ssSSP only result from binary interactions. For convenience, we call the difference a “discrepancy isochrone.” Here we show the discrepancy isochrones for a few stellar populations in Figures 2 and 3 for metal-poor ($Z = 0.004$) and solar metallicity ($Z = 0.02$) populations, respectively. Because we find that the discrepancy isochrones of metal-rich ($Z = 0.03$) populations are similar to those of solar metallicity populations, we do not show the results for metal-rich populations. Note that the results for populations with metallicities poorer than 0.004 are also given by our work, but we do not show them as the example for metal-poor populations, since the RPS model did not give the SEDs and Lick indices for populations with metallicities poorer than 0.004. This is actually limited by the spectral library used by the RPS model, which only supplies spectra for stars more metal-rich than 0.002. As we see, some special stars, e.g., blue stragglers, are generated by binary interactions (see also Fig. 1). We also show that the differences between isochrones of old bsSSPs and ssSSPs are smaller than those of young populations, because the isochrones of old populations are dominated by low-mass stars, in which binary interactions are much weaker.

3.2. The Effects on Integrated Features of Populations

The widely used integrated features of stellar populations are SEDs, Lick indices, and colors. They are usually used for stellar population studies and are important. We investigate the effects of binary interactions on them in this section.

3.2.1. Spectral Energy Distributions

To investigate how binary interactions affect the SEDs of stellar populations, we compare the SEDs of a bsSSP and an ssSSP that have the same age and metallicity. The differences between SEDs are simply called “discrepancy SEDs.” The absolute discrepancy SED for a bsSSP and ssSSP pair is derived by subtracting the flux of the ssSSP from that of the bsSSP as a function of wavelength. The discrepancy SEDs are mainly caused by blue stragglers and hot subdwarfs, as such stars are very hot and luminous. The changes of surface abundances of stars caused by binary interactions can also contribute to discrepancy SEDs. The absolute discrepancy SEDs for metal-poor ($Z = 0.004$) and solar metallicity...
(Z = 0.02) stellar populations are shown in Figures 4 and 5, respectively. The absolute discrepancy SEDs such as those shown in the figures can be easily used to add binary interactions into ssSSP models, but fractional discrepancy SEDs are more useful for understanding the effects of binary interactions. We show the fractional discrepancy SEDs of a few solar metallicity populations in Figure 6.

As we see, binary interactions make stellar populations less luminous, but the flux in short wave bands is changed by binary interactions weakly compared to that in long wave bands. This mainly results from special stars generated by binary interactions, which contribute differently to flux in different bands. The differences between the SEDs of a bsSSP and its corresponding ssSSP decrease with increasing age or decreasing metallicity. In addition, it suggests that binary interactions can affect most Lick indices and colors of populations, because the flux changes caused by binary interactions are not zero in the bands where widely used Lick indices and magnitudes are defined. In this case, bsSSP and ssSSP models usually give different results for stellar population studies. Furthermore, because the effects of binary interactions on the SED flux of populations are about 11% on average, they are detectable for observations with spectral signal-to-noise ratios (S/Ns) greater than 10. In other words, the effects can be detected by most observations, as most reliable observations have S/Ns greater than 10.

3.2.2. Lick Indices

Lick indices are the most widely used indices in stellar population studies, because they can disentangle the well-known (Z = 0.02) stellar populations are shown in Figures 4 and 5, respectively. The absolute discrepancy SEDs such as those shown in the figures can be easily used to add binary interactions into ssSSP models, but fractional discrepancy SEDs are more useful for understanding the effects of binary interactions. We show the fractional discrepancy SEDs of a few solar metallicity populations in Figure 6.

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3.2.2. Lick Indices

Lick indices are the most widely used indices in stellar population studies, because they can disentangle the well-known
stellar age-metallicity degeneracy (see, e.g., Worthey 1994). If binary interactions are taken into account, some results that are different from those determined via ssSSP models will be obtained, which was suggested by the study of the differences between the SEDs of bsSSPs and ssSSPs. Here we test how binary interactions change the Lick indices of stellar populations when compared to those of ssSSPs. In Figure 7 we show the differences between four widely used indices of bsSSPs and ssSSPs.

The indices are calculated from SEDs on the Lick system (Worthey et al. 1994) directly. As we see, Figure 7 shows that binary interactions make the Hβ index of a population larger by about 0.15 Å while making the Mg b index smaller by about 0.06 Å and Fe indices smaller by more than about 0.1 Å, compared to ssSSPs. Therefore, the changes in Lick indices are usually larger than typical observational uncertainties (about 0.07 Å for the Hβ index and 0.04 Å for metal-line indices, according to the data of Thomas et al. 2005). For fixed metallicity, the effects of binary interactions on both age- and metallicity-sensitive indices become stronger with increasing age when the stellar age is less than about 1.5–2 Gyr, and then the effects become weaker with increasing age. The reason is that binary interactions change the isochrones of populations most strongly near 1.5–2 Gyr as the first mass transfer between two components of binaries peaks, a lot of blue stragglers are generated near 1.5–2 Gyr according to the star sample of bsSSPs, and the light of old populations is dominated by low-mass binaries. The interactions between the two components of low-mass binaries are usually weaker than for high-mass binaries. The effects of binary interactions on the isochrones are tested quantitatively using the numbers of stars with log g < 4.0 and log $T_{\text{eff}}$ > 3.75, because these stars are very luminous and contribute a lot to the light of their populations. Our result shows that binary interactions change the number distribution of stars in the above log g and log $T_{\text{eff}}$ ranges most significantly when the stellar age is from 1.5 to 2 Gyr. In addition, from Figure 7 we find that for a fixed age, binary interactions affect the Hβ and Fe5270 indices of metal-poor populations more strongly than those of metal-rich populations, while they affect the Mg b and Fe5335 indices of metal-poor populations more weakly. As a whole, using ssSSPs and bsSSPs, various ages and metallicities will be measured for the same stellar population via popular Lick index methods such as the Hβ and [MgFe] method, which determines the ages and metallicities of populations by comparing the observational and theoretical Hβ and [MgFe] indices (Thomas et al. 2003). Note that the evolution of the differences between the Lick indices of ssSSPs and bsSSPs was not shown before.

3.2.3. Color Indices

Because colors are useful for estimating the ages and metallicities of distant galaxies (see, e.g., Li & Han 2008a), we investigate the effects of binary interactions on them. We use a method similar to that used for studying the Lick indices of stellar populations. Our detailed results are shown in Figure 8.

In the figure, the differences between two $UBVIJK$ colors, $B - V$ and $B - K$; a $ugriz$ color on the photometric system used by the Sloan Digital Sky Survey (SDSS), $u - r$; and a composite color, $r - K$, of bsSSPs and ssSSPs are shown. Note that the $r - K$ color consists of a Johnson system magnitude, $K$, and an SDSS magnitude, $r$. As we see, for a fixed age and metallicity, binary interactions make the colors of most stellar populations bluer than those predicted by ssSSPs. This mainly results from blue stragglers generated by binary interactions, because such stars are very luminous and blue. It suggests that we will get different stellar metallicities and ages for galaxies via bsSSP and ssSSP models using a photometric method. When comparing to the typical color uncertainties (0.12, 0.06, 0.13, 0.10, and 0.01 mag for $B$, $V$, $K$, $u$, and $r$ magnitudes, respectively), the changes (e.g., about $-0.04$, $-0.15$, and $-0.08$ mag for $B - V$, $B - K$, and $u - r$, respectively) of colors caused by binary interactions are similar to, but somewhat less than, typical observational errors. Note that the photometric uncertainties are estimated using the data of some publications, SDSS, and the Two Micron All Sky Survey (2MASS). The uncertainties actually depend on surveys. The observational uncertainties of the $u$ and $K$ magnitudes may be smaller when using the data of other surveys instead of those of SDSS and 2MASS. In addition, similar to Lick indices, the differences between the colors of the two kinds of stellar populations peak near 2 Gyr.

4. THE EFFECTS OF BINARY INTERACTIONS ON THE DETERMINATION OF STELLAR POPULATION PARAMETERS

Two stellar population parameters, i.e., stellar age and metallicity, are crucial in the investigations of the formation and
evolution of galaxies. We investigate the effects of binary interactions on the estimates of the two parameters. We try to fit the stellar population parameters of bsSSPs with various ages and metallicities using ssSSPs via both Lick index and photometric methods. Because observations show that about 50% of the stars in the Galaxy are in binaries, bsSSPs should be more similar to the real stellar populations of galaxies and star clusters. Therefore, the stellar population parameters fitted via ssSSPs (ss-fitted results, represented by $t_s$ and $Z_s$) should be different from the results obtained via bsSSPs (bs-fitted results, $t_b$ and $Z_b$). The detailed differences are shown in this section.

4.1. Lick Index Method

In a widely used method, i.e., the Lick index method, we fit the stellar ages and metallicities of populations by two indices, i.e., $H/\lambda C_{12}$ and $\text{[MgFe]} = \frac{\text{Mg}/(0.72\text{Fe} 5270 + 0.28\text{Fe} 5335)}{1/2}$, after Thomas et al. (2003). Thus, the results are slightly affected by $\alpha$-enhancement, and stellar population models (e.g., our RPS model) without any $\alpha$-enhancement compared to the Sun can be used to measure stellar population parameters. The differences between bs- and ss-fitted stellar population parameters of populations with four metallicities (0.004, 0.01, 0.02, and 0.03) and 150 ages (from 0.1 to 15 Gyr) are tested. In the test, we try to fit the stellar ages and metallicities of testing bsSSPs via an $H/\lambda$ versus $\text{[MgFe]}$ grid of ssSSPs. Because ssSSPs predict different Lick indices for populations compared to bsSSPs, when we use ssSSPs to fit the ages and metallicities of our testing bsSSPs, the results obtained are different from the real parameters of bsSSPs, i.e., bs-fitted parameters. From an $H/\lambda$ versus $\text{[MgFe]}$ grid of ssSSPs (Fig. 9), we can see this clearly.

In detail, the ss-fitted stellar ages are less than the bs-fitted ones by $\sim 5$ Gyr. The maximal difference is larger than the typical uncertainty ($< 2$ Gyr) in stellar population studies (see Fig. 9). The older the populations, the bigger the difference between ages fitted via bsSSPs and ssSSPs, although the differences between the Lick indices of old bsSSPs and ssSSPs are smaller (see § 3). The reason is that the differences among the Lick indices of populations with different ages are much less for old populations than for young populations (see Fig. 9 for comparison). Therefore, the ss-fitted ages of galaxies can be much less than the bs-fitted ages, because most galaxies, especially early-type ones, have old ($\sim 7\sim 8$ Gyr) populations, and their metallicities are not big (peak near 0.002; Gallazzi et al. 2005). However, ss-fitted metallicities of populations are similar to bs-fitted values, compared to the typical uncertainties ($\sim 0.002$). Therefore, if some stars are binaries, smaller ages will be measured via comparing the observational $H/\lambda$ and $\text{[MgFe]}$ indices of galaxies with those of theoretical ssSSPs. This is more significant for metal-poor stellar populations. In our testing populations, on average, the ss-fitted metallicities are 0.0010 poorer than the bs-fitted values, while the ss-fitted ages are younger than the bs-fitted values by 0.3 Gyr for all and 1.8 Gyr for old ($\geq 7$ Gyr) testing populations. In this work, the ss-fitted stellar ages and metallicities of testing bsSSPs are obtained by finding the best-fit populations in a grid of theoretical populations with intervals of stellar age and metallicity of 0.1 Gyr and 0.0001, respectively. A least-squares method is used in the fit. In addition, it is found that the bs-fitted ages of populations...
can be calculated from the ss-fitted ages and metallicities (with an rms of 1.45 Gyr) via the equation

\[ t_b = (0.17 + 8.27 Z_s) + (1.38 - 14.45 Z_s) t_s, \quad (2) \]

where \( t_b \), \( Z_s \), and \( t_s \) are the bs-fitted age and ss-fitted metallicity and age, respectively. The relation between bs-fitted ages and ss-fitted stellar population parameters can be seen in Figure 10.

We find that the ss-fitted ages are usually less than the bs-fitted ages of populations, and the poorer the metallicity, the larger the differences between the bs- and ss-fitted ages. Note that equation (2) is not very accurate for metal-poor (\( Z = 0.004 \)) and old (age >11 Gyr) populations. The reason is that the H/\( C_{12} \) index increases with age for metal-poor and old populations, while it decreases with age for other populations.

Fig. 8.—Differences between four colors of bsSSPs and ssSSPs. The differences in a color are calculated by subtracting the color of an ssSSP from that of its corresponding bsSSP (with the same age and metallicity). Symbols have the same meanings as in Fig. 6. The color \( u - r \) is on the SDSS \( ugriz \) system, and \( r - K \) is a composite color that consists of a Johnson magnitude (\( K \)) and a SDSS \( ugriz \) magnitude (\( r \)). The differences are averaged in each bin.

Fig. 9.—Some bsSSPs on the H/\( C_{12} \) vs. [MgFe] grid of ssSSPs. The letter “b” shows the bs-fitted age and metallicity of a bsSSP, and “s” shows the ss-fitted values for it. The composite index [MgFe] is calculated by [MgFe] = \([\text{Mg} b(0.72 \text{Fe}5270 + 0.28 \text{Fe}5335)]^{1/2}\) (Thomas et al. 2003). Dashed and solid lines indicate constant metallicity and constant age, respectively. Error bars show the typical observational uncertainties of the indices.

Fig. 10.—Relation between bs-fitted ages of bsSSPs and their ss-fitted stellar population parameters when using H/\( \beta \) and [MgFe] (Thomas et al. 2003) to measure the ages and metallicities of testing bsSSPs. Asterisks, circles, crosses, and squares represent stellar populations with real metallicities of 0.004, 0.01, 0.02, and 0.03, respectively. Solid, dash-dotted, dotted, and dashed lines show the fitted relations between the bs-fitted ages and ss-fitted results of populations for ss-fitted metallicities of 0.003, 0.009, 0.019, and 0.029, respectively.
4.2. Photometric Method

In the photometric method, we fit stellar population parameters via two pairs of colors, i.e., \((u/C0, R/C0)\) and \((u/C0, r/C0K)\). The two pairs are shown to have the ability to constrain the ages and metallicities of populations and can be used to study the stellar populations of some distant galaxies (see Li & Han 2008a). The test shows that the ss-fitted metallicities are poorer than the bs-fitted metallicities of populations. When using \((u/R, R/K)\) for this work, on average, ss-fitted metallicities are 0.003 smaller than bs-fitted values. They are 0.0035 smaller when using the pair \((u/r, r/K)\). The distribution of a few testing bsSSPs in the \(u/C0-T\) versus \(R/C0-K\) grid of ssSSPs is shown in Figure 11.

In particular, it is found that the ss-fitted ages are correlated with the bs-fitted ages of populations, which are independent of metallicity. The relation (with an rms of 0.72 Gyr) between ss- and bs-fitted ages of populations can be written as

\[
t_b = 0.24 + 0.93 t_s,
\]

where \(t_b\) and \(t_s\) are the bs- and ss-fitted ages, respectively. It shows that the bs- and ss-fitted ages are similar. The equation is clearly different from equation (2), because colors are usually less sensitive to metallicity compared with metal-line Lick indices. The relation between the bs- and ss-fitted ages of populations is shown in Figure 12.

The figure shows the approximate relation between the bs- and ss-fitted ages of populations, which is nearly independent of metallicity. The equation is possibly useful for estimating the absolute ages of distant galaxies and star clusters. Note that the relation is presented for populations younger than 14 Gyr, because the age of the universe is shown to be smaller than about 14 Gyr (Bennett et al. 2003).

When we use \(u/R\) and \(r/K\) colors to estimate the stellar population parameters of populations, we find that the ss-fitted metallicities are about 0.0035 smaller than the bs-fitted values. The bs- and ss-fitted ages of populations can be approximately transformed by

\[
t_b = 0.28 + 0.91 t_s,
\]

where \(t_b\) and \(t_s\) are the bs- and ss-fitted ages, respectively. The rms of the fitted relation is 1.00 Gyr. The equation is similar to equation (3) but with larger scatter. This results from the various metallicity and age sensitivities of the colors used. See Figure 13 for more details about the relation.

As a whole, from the results obtained by both Lick index and photometric methods, we are shown that bs-fitted stellar population parameters increase with ss-fitted ones. Therefore, using bsSSP models instead of ssSSP models obtains similar results for relative studies of stellar population parameters of galaxies. However, if one wants to get the absolute stellar population parameters of galaxies and star clusters, the effects of binary interactions should be taken into account, especially for metal-poor populations. This can be conveniently done by using the average metallicity deviations and the relations between the bs-fitted ages and ss-fitted results of populations, which are shown above.

4.3. Results for Populations with Chabrier Initial Mass Function

Some stellar populations with Salpeter IMFs (Salpeter 1955) were taken as standard models for the work, but even if some populations with other IMFs were taken instead, we can obtain similar results. We have a test using populations with the Chabrier
IMF (Chabrier 2003). The result shows that ss-fitted metallicities are 0.0011 less, on average, than bs-fitted results when using Hβ and [MgFe] for measuring stellar population parameters. The bs-fitted ages and ss-fitted stellar population parameters have a relation of $t_b = (-0.06 + 20.63 Z_s) + (1.46 - 18.76 Z_s) t_s$, where $Z_s$ is the ss-fitted metallicity and $t_b$ and $t_s$ are the bs- and ss-fitted ages, respectively. When we use $u - r$ and $R - K$ to estimate the stellar population parameters of populations, ss-fitted metallicities are shown to be 0.0031 smaller than bs-fitted values, and bs-fitted ages can be calculated from ss-fitted results via $t_b = 0.46 + 0.89 t_s$. A similar relation for the results fitted by $u - r$ and $r - K$ is $t_b = 0.41 + 0.88 t_s$, with a deviation of 0.0039 in metallicity. As a whole, the relations between bs- and ss-fitted results obtained via populations with Salpeter and Chabrier IMFs are similar, compared to the typical uncertainties of stellar population parameter studies. The comparisons of the results obtained via the two IMFs can be seen in Figures 12 and 13.

5. DISCUSSIONS AND CONCLUSIONS

We investigated the effects of binary interactions on the isochrones, SEDs, Lick indices, and colors of simple stellar populations (SSPs) and on the determination of luminosity-weighted stellar ages and metallicities. The results showed that binary interactions can affect stellar population synthesis studies significantly. In detail, binary interactions make stellar populations less luminous and bluer, while making the Hβ index larger and metal-line indices smaller compared to ssSSPs. The color changes (2%–5%) caused by binary interactions are smaller than the systematic errors (about 6%) of the RPS model while similar to the observational errors (4%–7%). Note that the systematic error of 6% did not take the uncertainties due to the free parameters of the star model into account (see § 2). The changes (3%–6%) of Lick indices caused by binary interactions are somewhat smaller than the systematic errors (about 6%) of the stellar population synthesis model but larger than the observational errors (1%–4%). Therefore, if we measure luminosity-weighted stellar population parameters (metallicity and age) via bsSSPs instead of ssSSPs, higher (0.0010, on average) metallicities and significantly larger ages will be obtained via a Lick index method, and significantly higher (about 0.0030) metallicities and similar ages will be obtained via a photometric method. Because SSP models are usually used for studying the populations of early-type galaxies or globular clusters, which possibly have old (>7 Gyr) and relatively metal-poor populations, the changes (~1.8 Gyr in age and 0.0030 in metallicity) caused by binary interactions in stellar ages and metallicities are larger than the typical uncertainties. In particular, we found that the relative results of stellar population studies obtained by ssSSPs and bsSSPs are similar. The bs-fitted stellar population parameters can be calculated from the ss-fitted ones via equations presented in this paper.

The relations between bs-fitted ages and ss-fitted stellar population parameters are useful for some special investigations. For example, when studying the age of the universe via the stellar ages of some distant globular clusters, we can estimate the absolute age of star clusters using ss-fitted results. Although the results shown in this paper can help us give some estimates for the absolute stellar ages and metallicities of galaxies, we are far from getting accurate values because of the large uncertainties in stellar population models (see, e.g., Yi 2003). In addition, different stellar population models usually give different absolute results for stellar population studies. Note that the results obtained by the Lick index method are affected slightly by α-enhancement, according to the work of Thomas et al. (2003), but this is not the case for the results obtained by photometric methods.

In this work, all bsSSPs contain about 50% binaries with orbital periods less than 100 yr (the typical value of the Galaxy). If the binary (with orbital periods less than 100 yr) fraction of galaxies is different from 50%, the results shown in the paper will change. The higher the fraction of binaries, the larger the difference between ss- and bs-fitted stellar population parameters. Thus, the results obtained in this paper may not be proper for investigating galaxies or star clusters with binary fractions obviously different from 50%. Furthermore, when building bsSSPs, we assumed that the masses of the two components of a binary are correlated (Li & Han 2008b), according to previous work. We did not try to use other distributions for secondary mass and binary period in this work, because we are limited by our present computing ability. We will conduct further studies in the future. The differences between the Lick indices and colors of bsSSPs and ssSSPs do not evolve smoothly with age. This possibly relates to the method used to calculate the integrated features of stellar populations. In fact, the Monte Carlo method usually leads to some scatter (about 2%) in the integrated features of populations. The analytic fits and the binary algorithm used by the Hurley code can also lead to some scatter (about 5%).

We investigated the effects of binary interactions only via some SSPs, but the real populations of galaxies and star clusters are usually not so simple. In other words, the populations of galaxies and star clusters seem to be composite stellar populations, including populations with various ages and metallicities (e.g., Yi et al. 2005). It seems that the effects of binary interactions and population mixing are degenerate. This is a complicated subject which requires further study.

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REFERENCES

Bennett, C. L., et al. 2003, ApJS, 148, 1
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Chabrier, G. 2003, ApJ, 586, L133
Davies, M., Piotto, G., & De Angeli, F. 2004, MNRAS, 349, 129
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Gallazzi, A., Charlot, S., Brinchmann, J., & White, S. 2005, MNRAS, 362, 41
Goldberg, D., & Mazeh, T. 1994, A&A, 282, 801
Han, Z., Podsiadlowski, P., & Eggleton, P. P. 1995, MNRAS, 272, 800
Han, Z., Podsiadlowski, P., & Lysas-Gray, A. E. 2007, MNRAS, 380, 1098
Hurley, J. R., Aarseth, S. J., & Shan, M. M. 2007, ApJ, 665, 707
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897
Kroupa, P., Tout, C. A., & Gilmore, G. 1993, MNRAS, 262, 545
Lejeune, T., Cuisinier, F., & Buser, R. 1998, A&A, 336, 65
Li, Z., & Han, Z. 2008a, MNRAS, 385, 1270
———. 2008b, MNRAS, 387, 105
Lodieu, N., Dobbie, P. D., Deacon, N. R., Hodgkin, S. T., Hambly, N. C., & Jameson, R. F. 2007, MNRAS, 380, 712
Martins, L. P., Delgado, R. M. G., Leitherer, C., Cerviño, M., & Hauschildt, P. 2005, MNRAS, 358, 49
Mazeh, T., Goldberg, D., Duquennoy, A., & Mayor, M. 1992, ApJ, 401, 265
Pinfield, D. J., Dobbie, P. D., Jameson, R. F., Steele, I. A., Jones, H. R. A., & Katsiyannis, A. C. 2003, MNRAS, 342, 1241
Pols, O., Hurley, J., & Tout, C. 1998, poster paper at IAU Symp. 191, Asymptotic Giant Branch Stars
Salpeter, E. E. 1955, ApJ, 121, 161
Thomas, D., Maraston, C., & Bender, R. 2003, MNRAS, 343, 279
Thomas, D., Maraston, C., Bender, R., & Mendes de Oliveira, C. 2005, ApJ, 621, 673
Tian, B., Deng, L., Han, Z., & Zhang, X. B. 2006, A&A, 455, 247
Tout, C. A., Aarseth, S. J., Pols, O. R., & Eggleton, P. P. 1997, MNRAS, 291, 732
Vazdekis, A. 1999, ApJ, 513, 224
Westera, P., Lejeune, T., Buser, R., Cuisinier, F., & Bruzual, G. 2002, A&A, 381, 524
Worthey, G. 1994, ApJS, 95, 107
Worthey, G., Faber, S. M., Gonzalez, J. J., & Burstein, D. 1994, ApJS, 94, 687
Xin, Y., Deng, L., & Han, Z. W. 2007, ApJ, 660, 319
Yi, S. K. 2003, ApJ, 582, 202
Yi, S. K., et al. 2005, ApJ, 619, L111
Yungelson, L., & Tutukov, A. 1997, in Advances in Stellar Evolution, ed. R. T. Rood & A. Renzini (Cambridge: Cambridge Univ. Press), 237
Zhang, F., Han, Z., Li, L., & Hurley, J. R. 2004, A&A, 415, 117
Zhang, F., Li, L., & Han, Z. 2005, MNRAS, 364, 503