Modeling of Integrated Spectral Energy Distributions of Stellar Populations with Various Binary Fractions

Zhongmu Li* and Chen Yan
Institute of Astronomy and History of Science and Technology, Dali University, Dali 671003, China

*Corresponding author email: zhongmuli@126.com

Abstract. Binary stars are common in the universe, but binary fractions are various in different star clusters and galaxies. Studies have shown that binary fraction affects the integrated spectral energy distributions obviously, in particular in the UV band. It affects spectral fitting of many star clusters and galaxies significantly. However, previous works usually take a fixed binary fraction, i.e., 0.5, and this is far from getting accurate results. Therefore, it is important to model the integrated spectral energy distributions of stellar populations with various binary fractions. This work presents a modeling of spectral energy distributions of simple stellar populations with binary fractions of 0.3, 0.7, and 1.0. The results are useful for different kinds of spectral studies.

Keywords: Stellar population, spectral energy distribution, binary.

1. Introduction
Most stars in the universe are possibly binary stars. The observation shows that the binary fraction of the Milky Way is at least 50 per cent, and it may be as large as 80 per cent. According to the studies of stellar evolution, binary stars with two close components evolve differently from single stars like the sun, because two components can exchange mass and energy in their evolution. There are many binary interactions between two components, and these interactions can lead to the formation of special stars such as blue stragglers, red stragglers, and hot sub-dwarfs. They also relate to the formation of Type Ia supernovae and gravitational waves. In particular, binary stars are confirmed to have significant effects on the formation of UV-upturn integrated spectral energy distributions (SEDs) of old stellar populations, e.g., some globular clusters and early-type galaxies. This finally leads to many changes of SED fitting. For example, the determination of stellar metallicity and age will change obviously when binary stars are taken into account, in SED, line index and color-magnitude diagram (CMD) studies. One can read many papers, e.g., Li et al. (2006, 2008a, 2008b, 2008c, 2012a, 2012b, 2013, 2016, 2018, 2020a, 2020b)[1–11], Conroy et al. (2014)[12], Han et al. (2007)[13], and Eldridge et al. (2017)[14] for more details.

Although binary stars have been taken into account by some stellar population studies, a binary fraction of 0.5 is usually used. For instance, it is used by the two most important binary stellar population synthesis groups, Yunnan and Brussels (see the review of Eldridge et al. 2017)[14]. In the SED fitting works of Zhang et al. (2004, 2005)[15,16], Li et al. (2006, 2008a, 2008b, 2008c, 2013)[1,2,3,4,7], half stars of a population are considered as binary stars. In fact, the binary fraction varies in star clusters and galaxies. This can be seen from the detailed studies of binary fractions of some nearby star clusters. The binary fraction range is very large from 0 to 100 per cent. In this case, it is not a good choice to take only a fixed binary fraction for various SED studies.
This work attempts to model the SEDs of simple stellar populations (SSPs) with different binary fractions. The results can be widely used for future SED studies, e.g., SED fittings and absorption index studies of star clusters and galaxies.

The second section introduces the parameter setting of SSP model. The third section analyzes the computation of stellar evolution and SEDs. The fourth section shows the main results of SED modeling of SSPs with various parameters. The last section summarizes the work done in this paper.

2. Inputs of SSP Models
Each SSP consists of 100,000 stars that have the same metallicity and age. The initial masses of stars are generated randomly following the initial mass function of Charbrier (2003)\(^{[17]}\), which is a piecewise function. The minimum and maximum masses of single stars are set to 0.1 and 100 \(M_\odot\). For binary stars, the masses of primary stars (\(M_1\)) are given by the same way as single stars, and the masses of secondary stars (\(M_2\)) are calculated by multiplying \(M_1\) by a mass ratio (\(q\)). Mass ratio \(q\) and orbital eccentricity (\(e\)) of binary stars are randomly generated in the range of 0–1. In order to check how metallicity and age affect the SEDs of SSPs, four metallicities and four ages are taken in the modeling. The detailed input parameters are listed in table 1.

| Font Spacing | Spacing |
|--------------|---------|
| Primary mass \(M_1\) | 0.1 – 100.0 \(M_\odot\) |
| Secondary mass \(M_2\) | < 100.0 \(M_\odot\) |
| Binary mass ratio \(q\) | 0 – 1 |
| Orbital eccentricity \(e\) | 0 – 1 |
| Metallicity \(Z\) | 0.0003, 0.001, 0.02, 0.03 |
| Binary fraction \(f_{bs}\) | 0.3, 0.7, 1.0 |
| Age \(t\) | 0.1, 5, 10, 13 Gyr |

3. Computation of Stellar Evolution and SEDs

3.1. Computation of Stellar Evolution
When building SSPs, both single and binary stars are evolved using a rapid stellar evolution code of Hurley et al. (2000, 2002)\(^{[18,19]}\). This code calculates the stellar evolutionary parameters based on some fitting formulae of accurate evolutionary tracks. There are two advantages to take this code. On one side, the computation is very fast. In fact, this is the fastest code to compute stellar evolution. It is therefore suitable to model stellar populations consisting of a large amount of stars. On another side, both single and binary stars can be evolved by this code. Because all galaxies and star clusters possibly contain some binary stars, it is necessary to include binary star evolution. Thus this code is suitable for our study.

3.2. Computation of SEDs
The SEDs of stellar populations are computed from the evolutionary parameters of stars. The main physics is that the spectrum of a star directly corresponds to its gravity and effective temperature. The correlation between spectrum and evolutionary parameters are given by spectral libraries. In this work, the BaSeL 3.1 spectral library (Lejeune et al. 1997, 1998)\(^{[20,21]}\) is used for computing the SEDs of stellar populations. The reason for choosing this library is that it covers enough wide wavelength range from UV to infrared. In addition, the uncertainty in the library is small.

4. SEDs of SSPs with Various Binary Fractions
This section shows the main results of SED modeling of SSPs with various parameters. The results of three binary fractions are presented in three sub-sections, respectively. The fluxes are plotted in the
same range to make it easy to compare the results.

4.1. SSPs with 30% Binary Stars
Figure 1 shows the SEDs of SSPs with a binary fraction of 0.3. As some examples, four metallicities ($Z = 0.0003, 0.001, 0.02, 0.03$) and four ages (0.1, 5, 10, 13 Gyr/s) are taken for the examples. As we see, when binary fraction and metallicity are fixed, SSPs become fainter when age increases. When binary fraction and age are fixed, SSPs become fainter with increasing metallicity.

![Figure 1. SEDs of SSPs with binary fraction of 0.3, four metallicities and four ages.](image)

4.2. SSPs with 70% Binary Stars
We find that SEDs changes with similar trends as the SSPs with a binary fraction of 0.3. Figure 2 shows the SEDs of SSPs with a binary fraction of 0.7.

![Figure 2. SEDs of SSPs with binary fraction of 0.7, four metallicities and four ages.](image)
4.3. SSPs with 100% Binary Stars
There are similar trends for the SEDs of SSPs when taking 100 per cent binary stars instead of 30 and 70 per cent, but the UV-upturn phenomenon is more obvious, in particular in the near UV band. Figure 3 shows the SEDs of SSPs with a binary fraction of 1.0.

5. Conclusion
This paper presents a modeling of SEDs of SSPs with various binary fractions. The SEDs of SSPs with binary fractions of 0.3, 0.7 and 1.0 have been shown. This is the first time to compare the SEDs of SSPs with different binary fractions, metallicities and ages. The results are important for SED studies of star clusters and galaxies.
We find that binary fraction affects the SEDs of SSPs clearly, in particular in the UV band. This means that UV SEDs are possibly useful for determining the binary fraction of star clusters and galaxies. In addition, we are shown that the effects of binary fractions, young stars, and metallicity are relatively degenerate. This suggests that there should be larger uncertainties in previous SED studies of the star formation histories, stellar ages, and extinctions of galaxies and star clusters.

According to our results, we suggest to take into account the following points in future SED studies of stellar populations:

- Stellar populations with different binary fractions should be used, in particular for old (> 5 Gyr) populations.
- The degeneracy between binary fraction and young population should be investigated deeper. This will help to get more accurate binary fractions and star formation histories of stellar populations.
- The effect of binary fraction on optical SED, line indices, and colors remains unclear and should be investigated further by future works.

Acknowledgments
Authors acknowledge that this work has been supported by the Yunnan Academician Workstation of Wang Jingxiu (No. 202005AF150025), National Natural Science Foundation of China (No. 11863002), and Sino-German Cooperation Project (No. GZ 1284).

References
[1] Li Z., Zhang F. and Han Z., A Study of Binary Stellar Population Synthesis of Elliptical Galaxies [J]. The Chinese Journal of Astronomy and Astrophysics, 2006, 6 (06): 669-679.
[2] Li Z. and Han Z., An isochrone data base and a rapid model for stellar population synthesis [J]. Monthly Notices of the Royal Astronomical Society, 2008a, 387 (01): 105-114.
[3] Li Z. and Han Z., How Binary Interactions Affect Spectral Stellar Population Synthesis [J]. The Astrophysical Journal, 2008b, 685 (01): 225-234.
[4] Li Z. and Han Z., The role of binary stars in stellar population synthesis [J]. Proceedings of the International Astronomical Union, 2008, 4 (252): 359-364.
[5] Li Z., Mao C., Chen L., and Zhang Q., Combined Effects of Binaries and Stellar Rotation on the Color-Magnitude Diagrams of Intermediate-age Star Clusters [J]. The Astrophysical Journal Letters, 2012a, 761 (02): L22.
[6] Li Z., Zhang L. and Liu J., Integrated spectral energy distributions of binary star composite stellar populations [J]. Monthly Notices of the Royal Astronomical Society, 2012b, 424 (02): 874-883.
[7] Li Z., Mao C., Chen L., Zhang Q. and Li M., The Potential Importance of Binary Evolution in Ultraviolet-Optical Spectral Fitting of Early-type Galaxies [J]. The Astrophysical Journal, 2013, 776: 37.
[8] Li Z., Mao C., Zhang L., Zhang X. and Chen L., A Systematic Study of Effects of Stellar Rotation, Age Spread, and Binaries on Color-Magnitude Diagrams with Extended Main-sequence Turnoffs [J]. The Astrophysical Journal Supplement Series, 2016, 225 (01): 7.
[9] Li Z. and Mao C., Evolution of Optical Binary Fraction in Sparse Stellar Systems [J]. The Astrophysical Journal, 2018, 859 (01): 36.
[10] Li Z., Spurzem R., Mao C., Ma Y. and Deng Y., A study of stellar population of intermediate-age globular cluster NGC 2249 [J]. Results in Physics, 2020a, 17: 103144.
[11] Li Z., Chen J., Zhang S., Deng Y. and Zhao W., Study of color-magnitude diagram of star cluster SL 506 [J]. Astrophysics and Space Science, 2020b, 365 (08): 134.
[12] Conroy C., Graves G. J., van Dokkum P. G., Early-type Galaxy Archeology: Ages, Abundance Ratios, and Effective Temperatures from Full-spectrum Fitting [J], The Astrophysical Journal, 2014, 780 (01): 33.
[13] Han Z., Podsiadlowski P. and Lynas-Gray A. E., Binary Stars as the Source of the Far-UV Excess in Elliptical Galaxies [J]. Monthly Notices of the Royal Astronomical Society, 2007, 380 (03): 1098-1118.
[14] Eldridge J. J., Stanway E. R., Xiao L., McClelland L. A. S., Taylor G., Ng M., Greis S. M. L. and Bray J. C., Binary Population and Spectral Synthesis Version 2.1: Construction, Observational Verification, and New Results [J]. Publications of the Astronomical Society of Australia, 2017, 34: e058.

[15] Zhang F., Han Z., Li L. and Hurley J. R., Evolutionary population synthesis for binary stellar populations [J]. Astronomy and Astrophysics, 2004, 415: 117-122.

[16] Zhang F., Han Z., Li L. and Hurley J. R., Inclusion of binaries in evolutionary population synthesis [J]. Monthly Notices of the Royal Astronomical Society, 2005, 357 (03): 1088-1103.

[17] Chabrier G., The Galactic Disk Mass Function: Reconciliation of the Hubble Space Telescope and Nearby Determinations [J]. The Astrophysical Journal Letters, 2000, 586 (02): L133-L136.

[18] Hurley J. R., Pols O. R., and Tout C. A., Comprehensive analytic formulae for stellar evolution as a function of mass and metallicity [J]. Monthly Notices of the Royal Astronomical Society, 2000, 315(3): 543-569.

[19] Hurley J. R., Tout C. A. and Pols O. R., Evolution of binary stars and the effect of tides on binary populations [J]. Monthly Notices of the Royal Astronomical Society, 2002, 329 (04), 897-928.

[20] Lejeune T., Cuisinier F. and Buser R., Standard stellar library for evolutionary synthesis. I. Calibration of theoretical spectra [J]. Astronomy and Astrophysics Supplement Series, 1997, 125: 229-246.

[21] Lejeune T., Cuisinier F. and Buser R., A standard stellar library for evolutionary synthesis. II. The M dwarf extension [J]. Astronomy and Astrophysics Supplement Series, 1998, 130: 65-75.