Inclusion of sdBs in evolutionary population synthesis for binary stellar populations and the application: the determinations of photo-z and galaxy morphology

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Abstract Subdwarf B stars (sdBs) can significantly change the ultraviolet spectra of populations at age $t \sim 1$ Gyr, and have been even included in the evolutionary population synthesis (EPS) models by Han et al. (2007). In this study we present the spectral energy distributions (SEDs) of binary stellar populations (BSPs) by combining the EPS models of Han et al. (2007) and those of the Yunnan group (Zhang et al. 2004, 005), which have included various binary interactions (except sdBs) in EPS models. This set of SEDs is available upon request from the authors.

Using this set of SEDs of BSPs we build the spectra of Burst, E, S0, Sa-Sd, and Irr types of galaxies. Combining them with the photometric data (filters and magnitudes), we obtain the photometric redshifts and morphologies of 1502 galaxies by using the Hyperz code of Bolzonella et al. (2000). This sample of galaxies is obtained by removing those objects, mismatched with the SDSS/DR7 and GALEX/DR4, from the catalogue of Fukugita et al. (2007). By comparison the results with the SDSS spectroscopic redshifts and the morphological index of Fukugita et al. (2007), we find that the photo-zs fluctuate with the SDSS spectroscopic redshifts, while the Sa-Sc galaxies in the catalogue of Fukugita et al. (2007) are classified earlier as Burst-E galaxies.

Keywords Galaxies: distance and redshifts - Galaxies: fundamental parameters - binary: general - stars: horizontal branch - ultraviolet: galaxies

1 Introduction

Binary interactions play an important role in evolutionary population synthesis (EPS) models, and their inclusion can affect the overall shape of the spectral energy distribution (SED) of population. In particular, the SED in the ultraviolet passbands is bluer by 2-3 magnitude at $t \sim 1$ Gyr if binary interactions are included. The bluer SED in the ultraviolet passbands is caused by those binary interactions which can create some important classes of objects, such as hot subdwarf B stars (sdBs) for a population older than $\sim 1$ Gyr (Han, Podsiadlowski & Lynas-Gray 2007, hereafter HPL07) and blue stragglers at 0.5-1.5 Gyr.

The Yunnan group (Zhang et al. 2004, 2005) has included various binary interactions in EPS models and has presented the SEDs and colours for an extensive set of binary stellar populations (BSPs), however, it has neglected sdBs. Recently, Han et al. (2002, 2003) proposed a binary model for the formation of hot sdBs in binaries and single hot sdBs (three formation channels), and HPL07 presented the SEDs of populations with the binary interactions of sdBs. In this study we will present the new set of SEDs (HPL07+Yunnan models) for BSPs by combining the EPS models of HPL07 with those of Yunnan models.

As an application of this new set of SEDs of BSPs, firstly, we build the spectra of Burst, E, S0, Sa-Sd, and Irr types of galaxies. Combining them with the Galaxy Evolution Explorer (GALEX) $F_{UV}$, $N_{UV}$, Sloan...
we obtain their photometric redshifts (photo-zs) and morphologies by using the Hyperz code of Bolzonella, Miralles & Pello (2000). These galaxies are from the catalogue of Fukugita et al. (2007) and matched with the GALEX Data Release four (DR4) and SDSS Data Release seven (DR7). The outline of the paper is as follows. In Section 2 we present the new set of SEDs of BSPs. In Section 3 we apply this set of SEDs to the determinations of photo-z and galaxy morphology.

2 Inclusion of sdBs in EPS for BSPs

In this study we use the standard HPL07 and Yunnan EPS models. In the standard Yunnan models are the following assumptions: (i) the initial mass-ratio distribution satisfies a uniform value, i.e., \( n(q) = 1 \); (ii) the common envelope (CE) ejection efficiency \( \alpha'_{\text{CE}} = 3.0 \), which is introduced with the following criterion (in the CE evolution model): the CE is ejected when the change in orbital energy \( \Delta E_{\text{orb}} \), multiplied by \( \alpha'_{\text{CE}} \), exceeds the change in binding energy of the envelope \( \Delta E_{\text{bind}} \); and (iii) the Reimers wind mass-loss coefficient \( \eta \) is 0.3. The ages of BSPs are in the range \( 5.0 \leq \log(t/\text{yr}) \leq 10.2 \), and the metallicities are in the range \(-2.3 \leq [\text{Fe/H}] \leq 0.3\).

In the standard HPL07 models, we have the following: (i) \( n(q) = 1 \); (ii) the critical mass ratio \( q_c \) is 1.5 above which the first Roche lobe overflow on the first giant branch or asymptotic giant branch is unstable; and (iii) \( \alpha_{\text{CE}} = 0.75 \) and \( \alpha_{\text{th}} = 0.75 \), assuming that when \( \alpha_{\text{CE}} \cdot \Delta E_{\text{orb}} + \alpha_{\text{th}} \cdot \Delta E_{\text{th}} \) (the change in thermal energy of the envelope) exceeds \( \Delta E_{\text{bind}} \), the CE is ejected. In this prescription the thermal energy of the envelope is considered. The HPL07 models are only for solar-metallicity populations, and the ages of populations are in the range \( 8.0 \leq \log(t/\text{yr}) \leq 10.2 \).

Combining the EPS models of the Yunnan group with those of HPL07, we obtain a new set of SEDs for solar-metallicity BSPs (hereafter Yunnan+HPL07 models). The ages are in the range \( 5.0 \leq \log(t/\text{yr}) \leq 10.2 \) at a logarithmic age interval of 0.05 or 0.1.

In Figs. 1 and 2 we give the SED at age \( \log(t/\text{yr}) = 9.50 \) and the evolution of GALEX \( F_{\text{UV}} \) magnitude of a solar-metallicity population with a mass of \( 1M_\odot \) for Yunnan, HPL07 and HPL07+Yunnan models. From it we see that the ultraviolet spectra and \( F_{\text{UV}} \) magnitude of HPL07+Yunnan models are significantly bluer than those of the Yunnan and HPL07 models at late ages.

3 Application to the determination of photo-z and galaxy morphology

In this part we use this set of SEDs to determine redshift and galaxy morphology. In Sections 3.1 and 3.2 we describe the method and the galaxy sample, respectively. In Section 3.3 we present the results and the comparisons.

3.1 Method

The photo-z is computed through the Hyperz code of Bolzonella et al. (2000), which adopts a standard SED fitting method:

\[
\chi^2 = \sum_{i=1}^{N_{\text{filters}}} \frac{\left[ F_{\text{obs},i} - b \times F_{\text{temp},i} \right]^2}{\sigma_i^2}
\]
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### 3.2 Sample and data

Our initial sample of galaxies is from the catalogue of Fukugita et al. (2007), which contains 2253 galaxies with Petrosian magnitude \( r_p \) brighter than 16 mag in the north equatorial stripe from the SDSS/DR3. Removal of the objects mismatched with the SDSS DR7 and GALEX DR4 produces a final sample of 1502 galaxies. The matching radius between SDSS/DR7 and GALEX/DR4 is 6.0 arcsec, and the nearest neighbour is taken as a true association if its radius is smaller than the matching radius.

From the catalogue of Fukugita et al. (2007) we get their morphological classification which is obtained by visual inspection of images in the \( g \) band. From the SDSS/DR7 and GALEX/DR4 we obtain the SDSS spectroscopic redshifts, \( F_{\text{UV}}, N_{\text{UV}}, u, g, r, i, \) and \( z \) magnitudes and their errors for these galaxies.

3.3 Results concerning the photo-zs and morphologies of galaxies

Inputting the magnitudes (and their errors) of the 1502 galaxies, the filter set and the template spectra in the \textit{Hyperz} code, we obtain their photo-zs and morphologies. In Fig. 4 we give the comparison between the SDSS spectroscopic \( z_{\text{spec}} \) and the derived photometric \( z_{\text{phot}}^{\text{UVV}} \) redshifts for 1502 galaxies. Dotted-dashed line corresponds to \( \delta z = 0.2 \). Red, black, green and purple symbols denote galaxies with the \( z_{\text{phot}}^{\text{UVV}} \) probability: \( p(\chi^2) \geq 99, 99 > p(\chi^2) \geq 90, 90 > p(\chi^2) \geq 68 \) and \( p(\chi^2) < 68 \).

In Fig. 5 we give the comparison between our derived morphological index \( T(\text{Ours}) \) with those of Fukugita et al., 2007, \( T(\text{Fuk}) \). The corresponding galaxy types of \( T(\text{Ours}) \) and \( T(\text{Fuk}) \) are presented in Table 1. Note in the catalogue of Fukugita et al. (2007) the half-integer classes are allowed for. From the comparison we see that the early-type galaxies can be easily and reliably retrieved, while Sa-Sc galaxies in the catalogue of Fukugita et al. (2007) are often classified somewhat earlier, as Burst-E in our classifications. This is caused by that at \( z \leq 0.2 \) no spectral signature can be used in...
Fig. 5 Comparison of our $T$ with those of Fukugita et al. for 1502 galaxies. The area of the circle represents the number of galaxies in the grid. Crosses show the correlation in the definition $T$ between ours and Fukugita et al. (2007). The area of circle located in the upper left corner denotes $N = 10$.

the Hyperz code, thus leading to the degeneracy among the fit parameters.

On the whole from the comparisons in Figs. 4 and 5 we conclude that the photo-zs and the early types of bright galaxies can be reliably obtained, while the late types are often misidentified as early types. Meanwhile, other objects (such as, blue stragglers) from binary interactions also can affect the determination of the photometric redshifts and morphologies of galaxies.

4 Summary

In this study we present the SEDs of solar-metallicity BSPs by combining the EPS models of HPL07 and the Yunnan group. The set of SEDs is available on request from the authors. Inclusion of sdBs makes the spectra in the ultraviolet passband bluer at late ages.

Using this set of SEDs of BSPs and Hyperz code we obtain the photo-zs and morphologies of 1502 galaxies. This sample of galaxies is obtained by removing those objects mismatched with SDSS/DR7 and GALEX/DR4 from the catalogue of Fukugita et al. (2007). By comparing the derived photo-zs with SDSS spectroscopic redshifts we find that the photo-zs fluctuate around the spectroscopic values. By comparing the morphological index with those of Fukugita et al. (2007) we find that the Sa-Sc galaxies in their catalogue are classified earlier in this study. This maybe implies that we should add other feature(s) or structural parameters, which can be separate early-type galaxies from spirals in advance, in the galaxy morphology determination.

Table 1  Morphological index $T$ of Fukugita et al. (2007) and Ours.

| galaxy Type | $T$(Fuk) | $T$(Ours) |
|-------------|----------|-----------|
| Unclassified | -1 | ... |
| Burst | ... | 1 |
| E | 0 | 2 |
| S0 | 1 | 3 |
| Sa | 2 | 4 |
| Sb | 3 | 5 |
| Sc | 4 | 6 |
| Sd | 5 | 7 |
| Irr | 6 | 8 |
| CWW-E | ... | 9 |
| CWW-Sbc | ... | 10 |
| CWW-Scd | ... | 11 |
| CWW-Irr | ... | 12 |

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