Colour pairs for constraining the age and metallicity of stellar populations

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ABSTRACT

Using a widely used stellar-population synthesis model, we study the possibility of using pairs of AB system colours to break the well-known stellar age–metallicity degeneracy and to give constraints on two luminosity-weighted stellar-population parameters (age and metallicity). We present the relative age and metallicity sensitivities of the AB system colours that relate to the $u$, $B$, $g$, $V$, $r$, $R$, $i$, $I$, $z$, $J$, $H$ and $K$ bands, and we quantify the ability of various colour pairs to break the age–metallicity degeneracy. Our results suggest that a few pairs of colours can be used to constrain the above two stellar-population parameters. This will be very useful for exploring the stellar populations of distant galaxies. In detail, colour pairs $[(r–K), (u–R)]$ and $[(r–K), (u–r)]$ are shown to be the best pairs for estimating the luminosity-weighted stellar ages and metallicities of galaxies. They can constrain two stellar-population parameters on average with age uncertainties less than 3.89 Gyr and metallicity uncertainties less than 0.34 dex for typical colour uncertainties. The typical age uncertainties for young populations (age $\leq 4.6$ Gyr) and metal-rich populations ($Z \geq 0.001$) are small (about 2.26 Gyr) while those for old populations (age $\geq 4.6$ Gyr) and metal-poor populations ($Z < 0.001$) are much larger (about 6.88 Gyr). However, the metallicity uncertainties for metal-poor populations (about 0.0024) are much smaller than for other populations (about 0.015). Some other colour pairs can also possibly be used for constraining the two parameters.

On the whole, the estimation of stellar-population parameters is likely to be reliable only for early-type galaxies with small colour errors and globular clusters, because such objects contain less dust. In fact, no galaxy is totally dust-free and early-type galaxies are also likely have some dust [e.g. $E(B–V) \sim 0.05$], which can change the stellar ages by about 2.5 Gyr and metallicities ($Z$) by about 0.015. When we compare the photometric estimates with previous spectroscopic estimates, we find some differences, especially when comparing the stellar ages determined by two methods. The differences mainly result from the young populations of galaxies. Therefore, it is difficult to obtain the absolute values of stellar ages and metallicities, but the results are useful for obtaining some relative values.

In addition, our results suggest that colours relating to both $UBVRIJHK$ and $ugriz$ magnitudes are much better than either $UBVRIJHK$ or $ugriz$ colours for breaking the well-known degeneracy. The results also show that the stellar ages and metallicities of galaxies observed by the Sloan Digital Sky Survey and the Two-Micron All-Sky Survey can be estimated via photometry data.

Key words: galaxies: elliptical and lenticular, cD – galaxies: photometry – galaxies: stellar content.

1 INTRODUCTION

The formation and evolution of galaxies is one of the hottest topics in astronomy and astrophysics, and there has been great progress in the field (see, for example, Kormendy & Djorgovski 1989; Thomsen & Baum 1989; Baugh, Cole & Frenk 1996; Baugh et al. 1998; Kauffmann & Charlot 1998; Kodama et al. 1998; Thomas 1999;
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2 BC03 MODEL AND CALCULATION OF COLOURS

The BC03 model is a widely used model in stellar-population synthesis study. Its standard model takes the Chabrier (2003) initial mass function (IMF) and uses Padova 1994 library tracks to calculate integrated colours. A few alternative stellar spectral libraries are considered to give the spectral predictions of simple stellar populations (SSPs). The model provides us with magnitudes and colours considered to give the spectral predictions of simple stellar populations.

Table 1. Relative metallicity sensitivities of 66 AB system colours.

| Colour | rms | Colour | rms |
|--------|-----|--------|-----|
| (B–K)  | 2.0294 | (i–z) | 0.8218 |
| (R–K)  | 1.8610 | (i–K) | 0.8094 |
| (u–K)  | 1.6904 | (g–i) | 0.7863 |
| (I–J)  | 1.6125 | (B–r) | 0.7554 |
| (V–K)  | 1.5774 | (B–R) | 0.7335 |
| (r–K)  | 1.4114 | (V–I) | 0.7237 |
| (i–J)  | 1.4031 | (g–r) | 0.7027 |
| (I–K)  | 1.2654 | (r–G) | 0.6952 |
| (R–J)  | 1.2160 | (V–R) | 0.6896 |
| (g–J)  | 1.1094 | (V–r) | 0.6877 |
| (B–z)  | 1.0914 | (u–I) | 0.6725 |
| (u–J)  | 1.0474 | (r–I) | 0.6722 |
| (B–J)  | 1.0455 | (r–B) | 0.6675 |
| (V–J)  | 1.0145 | (u–B) | 0.6632 |
| (v–z)  | 1.0069 | (r–c) | 0.6534 |
| (g–w)  | 0.9985 | (g–z) | 0.6404 |
| (z–w)  | 0.9805 | (r–I) | 0.6382 |
| (g–K)  | 0.9719 | (u–H) | 0.6320 |
| (r–J)  | 0.9247 | (i–z) | 0.6151 |
| (B–i)  | 0.8789 | (u–i) | 0.5909 |
| (V–i)  | 0.8719 | (I–H) | 0.5867 |
| (B–I)  | 0.8414 | (g–I) | 0.5856 |

3 AGE AND METALLICITY SENSITIVITIES OF COLOURS

We study the age and metallicity sensitivities using a relative metallicity sensitivity (rms) technique, which was used by Worthey (1994) and Li et al. (2007), and we find age- and metallicity-sensitive colours based on the rms of colours. The rms method estimates the rms of each colour by the ratio of percentage change of age to that of metallicity when they lead to the same change in a colour respectively. Colours with large rms (>1.0) are more sensitive to metallicity and those with small rms (<1.0) to stellar age. Following Li et al. (2007), we calculated the rms of each colour in this work.

The rms of 66 AB system colours is calculated in the work. The detailed data are listed in Table 1. As can be seen, (B–K), (R–K), (u–K), (I–J), (V–K), (r–K), (i–J), (I–K), (R–J) and (g–J) are more sensitive to stellar metallicity while (J–H), (i–I), (R–H), (z–K), (V–I), (u–R), (B–V), (B–g), (u–r) and (g–H) are more sensitive to stellar age. We select the former 10 colours as age-sensitive colours while the latter 10 are metallicity-sensitive colours.

4 COLOUR PAIRS FOR BREAKING THE AGE–METALLICITY DEGENERACY

4.1 Colour pairs for general studies

Using the 10 metallicity-sensitive colours and the 10 age-sensitive colours presented in the last paragraph of Section 3, we build up 100 colour pairs. Each colour pair includes a metallicity-sensitive colour and an age-sensitive colour. Using the colour pairs one by one, we fit the stellar ages and metallicities of 500 testing stellar populations. To make the results useful for estimating the parameters of all types of stellar populations, the ages and metallicities of the testing populations are generated randomly within the ranges of 0.1–15 Gyr and 0.0001–0.05, respectively. The averages of uncertainties in age and metallicity (Δτ and ΔZ) are then calculated by taking

1 See http://www.astro.livjm.ac.uk/~ikb/convert-units/node1.html.
typical uncertainties for input colours. The typical uncertainties for $U, B, V, R, I, I, H, K, u, g, r, i$ and $z$ magnitudes are taken as 0.109, 0.116, 0.059, 0.03, 0.07, 0.08, 0.09, 0.126, 0.11, 0.01, 0.007, 0.007 and 0.012 mag, respectively. These values are estimated using the data supplied by the NASA/IPAC Extragalactic Database (NED), the 2MASS and SDSS surveys. Then we investigate the ability of each colour pair to break the well-known stellar age–metallicity degeneracy by comparing $\Delta t$ and $\Delta Z$. A least-squares method is used to fit the ages and metallicities of stellar populations in the work. The uncertainties in stellar-population parameters are estimated by taking the maximum uncertainties in the two parameters when considering the uncertainties of colours. Please refer to Denicoló et al. (2005) or Li et al. (2006) for more details. The main results are listed in Table 2.

Because colour pairs that are well able to break the stellar age–metallicity degeneracy lead to small uncertainties in stellar age and metallicity, pairs with small $\Delta t$ and $\Delta Z$ are better for constraining two stellar-population parameters. However, as can be seen, some colour pairs have only small $\Delta t$ or small $\Delta Z$. In this case, it is difficult to compare the abilities of various colour pairs. We have defined a parameter, the uncertainty parameter ($UP$), to solve this problem. The $UP$ is calculated by taking the average of the relative uncertainties of stellar ages and metallicities of the 500 testing stellar populations. According to the calculation of $UP$, colour pairs with small $UP$ are more suitable for breaking the stellar age–metallicity degeneracy. The $UP$s of colours are shown in Table 2, together with $\Delta t$ and $\Delta Z$. Considering actual applications, we only list the results of colour pairs that have $UP$ smaller than 2.0 when taking typical uncertainties for colours. In the table, colours are sorted by an increasing order of $UP$. Note that we also list the average metallicity uncertainty in dex. As can be seen, $[\{(r-K),(u-R)\}]$ and $[\{(r-K),(u-R)\}]$ are the best colour pairs for breaking the well-known degeneracy.

Given typical uncertainties for colours, the two colour pairs can constrain stellar-population parameters with relative uncertainties smaller than about 96 per cent, which corresponds to average uncertainties in stellar age and metallicity smaller than 3.89 Gyr and 0.34 dex, respectively. Some other pairs, that is, $[(R-K),(u-R)], [(I-K),(u-R)], [(R-K),(u-R)]$ and $[(i-J),(u-R)]$, can possibly be used to give constraints on the stellar ages and metallicities of galaxies, because they have small $UP$ ($\leq 1.13$) for typical uncertainties of colours. In addition, colour pairs relating to both $UBVRIJHK$ and $ugriz$ bands are shown to be much better than those only relating to one of the two types of bands. To illustrate the abilities of colour pairs to break the age–metallicity degeneracy, we show the colour–colour grids of four pairs in Fig. 1.

However, as noted from Table 2, the uncertainties in two stellar-population parameters are very large. This results from the large observational uncertainties. Because the observational uncertainties depend on surveys and because they will possibly be decreased in future surveys, we have tried to find the best pairs for various uncertainties (0.02, 0.05 and 0.10) in colours. We assumed that all colours have the same uncertainty in each test. The results are shown in Table 2. As can be seen, if the uncertainties of colours are less than 0.05 mag, the stellar ages and metallicities of galaxies can be constrained with uncertainty less than 1 Gyr and 0.0076, respectively, using $(I-K)$ and $(u-R)$.

### 4.2 Colour pairs for special studies

Because we often need to estimate the ages and metallicities of some special stellar populations (e.g. old populations of globular clusters), we have tried to find some colour pairs that are suitable for estimating the two luminosity-weighted stellar-population parameters of such populations. In detail, the best colour pairs for estimating...
the stellar ages and metallicities of young ($t < 4.6$ Gyr), old ($t \geq 4.6$ Gyr), metal-poor ($Z < 0.001$) and metal-rich ($Z \geq 0.001$) stellar populations are found by taking the above typical uncertainties of colours. Table 3 lists the best 10 colour pairs for studying each type of special population. As can be seen, there are various colour pairs for studying different types of stellar populations. However, \([r-K], (u-r)\] can be used to constrain the age and metallicity of all types of stellar populations. We also find that when colour pair \([r-K], (u-r)\] is used to study the stellar-population parameters of various populations, the uncertainties of the results are different. The age uncertainties of old or metal-poor populations are usually larger than those of young or metal-rich populations.

\subsection*{4.3 Composite colour pairs}

In practice, we can also use colour pairs including magnitudes on different systems, because colours relating to the same bands but on different systems usually have similar properties for breaking the well-known stellar age–metallicity degeneracy (Worthey 1994). For example, we can use colour pair \([r-K], (u-r)\), in which \(ur\) magnitudes are on the AB system and the \(K_i\) magnitude on the 2MASS system, instead of \([r-K], (u-r)\), in which all magnitudes are on the AB system. Of course, we can use the Johnson–Cousins–Glass system colours together with AB system colours.

Table 3. Best colour pairs for estimating the ages and metallicities of old ($Z \geq 0.001$) and metal-poor ($Z < 0.001$) stellar populations. Symbols have the same meanings as in Table 2. The values are calculated using the typical colour uncertainties. Note that the age uncertainties of metal-poor populations are not always correct because some test populations are out of the colour–colour grid when taking their colour uncertainties into account.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
\textbf{Colour pair} & \textbf{Old population} & % & % & & \textbf{Young or metal-rich population} & % & % & & \textbf{Metal-poor population} & % & % & \\
\hline
\([r-K], (u-r)\] & 6.88 & 0.141 & 0.73 & & \([r-K], (u-r)\] & 2.26 & 0.0174 & 0.76 & & \([r-K], (u-r)\] & 3.64 & 0.0024 & 4.96 \\
\([i-J], (u-r)\] & 7.17 & 0.0146 & 0.73 & & \([i-J], (u-r)\] & 1.34 & 0.0222 & 0.78 & & \([r-K], (u-r)\] & 3.98 & 0.0024 & 4.96 \\
\([i-J], (u-K)\] & 7.58 & 0.0149 & 0.75 & & \([i-J], (u-R)\] & 1.43 & 0.0220 & 0.81 & & \([R-K], (u-R)\] & 4.10 & 0.0026 & 5.52 \\
\([r-K], (u-R)\] & 7.51 & 0.0144 & 0.76 & & \([r-K], (u-R)\] & 2.54 & 0.0173 & 0.81 & & \([g-J], (z-K)\] & 1.85 & 0.0032 & 5.69 \\
\([R-K], (u-r)\] & 8.17 & 0.0170 & 0.89 & & \([R-K], (u-r)\] & 2.70 & 0.0195 & 0.85 & & \([R-K], (u-r)\] & 3.89 & 0.0030 & 5.79 \\
\([R-K], (u-R)\] & 8.47 & 0.0174 & 0.91 & & \([R-K], (u-R)\] & 2.64 & 0.0195 & 0.86 & & \([B-K], (z-K)\] & 3.67 & 0.0032 & 6.18 \\
\([V-K], (u-R)\] & 9.57 & 0.0188 & 1.07 & & \([V-K], (u-R)\] & 2.43 & 0.0216 & 0.93 & & \([i-J], (B-V)\] & 3.42 & 0.0031 & 6.23 \\
\([i-J], (i-I)\] & 11.29 & 0.0177 & 1.10 & & \([i-J], (u-R)\] & 2.46 & 0.0235 & 0.95 & & \([u-K], (z-K)\] & 6.33 & 0.0029 & 6.26 \\
\([V-K], (u-R)\] & 9.19 & 0.0187 & 1.13 & & \([i-J], (u-R)\] & 2.50 & 0.0235 & 0.96 & & \([i-J], (B-V)\] & 3.87 & 0.0030 & 6.47 \\
\([i-J], (z-K)\] & 9.79 & 0.0170 & 1.16 & & \([R-J], (u-R)\] & 2.29 & 0.0250 & 1.06 & & \([r-K], (B-V)\] & 3.44 & 0.0031 & 6.67 \\
\hline
\end{tabular}
\end{table}
first 10 galaxies of our sample, which are marked in black. We see that a rough estimation can be obtained for the two parameters of galaxies, although the uncertainties are large. As examples, we list the stellar-population parameters of a few galaxies in Table 4, in which the data of three subsets of galaxies are listed. In fact, even if we take Lick indices for such work, the uncertainties in stellar ages and metallicities of these galaxies are very large because of the large observational uncertainties. For our sample galaxies, the uncertainties in Hβ and [MgFe] indices are typically about 0.3 Å, which will lead to large uncertainties in stellar-population parameters. The Lick indices and uncertainties of our sample galaxies are taken from the Garching SDSS catalogues. Furthermore, we found that 24 galaxies are out of the theoretical grid of the BC03 models. This possibly results from the effects of young stellar populations (YSPs) of galaxies, the limitation of theoretical models and large observational uncertainties of colours. In particular, we found that most galaxies fall inside the theoretical colour–colour grid when taking their colour uncertainties into account. This means that most of the 24 galaxies could have physical ages but, as pointed out by Li et al. (2007), the presence of young populations in such early-type galaxies can also make metal-rich populations outside the theoretical colour–colour grids.

In this work, we fitted the stellar ages and metallicities of our sample galaxies using BC03 SSPs with ages within 0.1–19.96 Gyr and metallicities within 0.0001–0.05. In Fig. 3, we compare the parameters determined by colours with those by a few Lick indices (Gallazzi et al. 2005). The results of Gallazzi et al. (2005) were obtained by comparing D4000, Hβ, Hβ + Hα, [MgFe] and [MgFe]' indices of galaxies with the values of theoretical stellar populations. We have taken the effects of YSPs into account. In future, detailed data about the sample galaxies can be obtained on request to the authors or via the CDS. From Figs. 3(a) and (c), we find that the stellar ages and metallicities determined by colours are respectively smaller and richer than those determined by Lick indices. This is because there are composite stellar populations (CSPs) in galaxies and the YSPs make the results derived from colours biased to be younger and richer in metal compared to those of the dominant stellar populations (DSPs) of galaxies (Li & Han 2007). In detail, because the age of a YSP affects the colours of a star system more strongly than the mass fraction of the YSP, YSPs with only a few per cent stellar mass can make the colour-fitted stellar populations younger and more metal-rich than the DSPs of galaxies if the YSPs are not too old. In Figs. 3(b) and (d), we compare the stellar-population parameters measured by colours and corrected for the effects of YSPs to those determined by Lick indices. The correction is accomplished using the possible distributions of the differences between the stellar-population parameters of the DSPs and CSPs and the parameters derived from the two colours of CSPs (Li & Han 2007). The above distributions were obtained using a statistical method, in which the fractions of YSPs were assumed to depend on the ages of the DSPs and YSPs, and the fraction of a YSP was assumed to decline exponentially with decreasing age of the YSP (see, for example, Thomas, Maraston & Bender 2005). In particular, the distributions can be used to give a rough correction for the effects of YSPs. Here, we obtain the corrected stellar age of a galaxy by submitting from the colour-fitted result a random value that fits the distribution of the difference between the stellar ages of DSPs and those derived from two colours. A similar method is used to obtain the corrected stellar metallicities. For more clarity, we show the

![](https://academic.oup.com/mnras/article-abstract/385/3/1270/1010054/1274_Z.Li_and_Z.Han)

**Figure 2.** Our sample galaxies (1646 galaxies) in the (u−r) versus (r−K) grid. The error bars give the typical colour uncertainties of galaxies. Lines have the same meanings as in Fig. 1. Here, we have not marked the constant ages of 8 and 16 Gyr.

In this work, we analysed colour pairs relating to five AB system bands (ugriz) and three 2MASS bands (JHKs). According to the results, colour pairs [(u−r), (r−K)], [(u−r), (i−J)] and [(u−K), (z−K)] are more suitable for constraining stellar-population parameters than others. Because (r−K) and (u−K) have almost the same ability for determining stellar population parameters as (r−K) and (u−K), the UP of the three colour pairs can refer to Table 2. Because these pairs have colour–colour grids similar to those shown in Fig. 1, we do not show them here.

5 APPLICATION OF COLOURS AND COLOUR PAIRS

5.1 Using colour pairs to constrain stellar-population parameters

To test whether colour pairs can be used to estimate the ages and metallicities of stellar populations, we select 1646 luminous (absolute magnitude $M_r < -22$ and r-band Petrosian magnitude $< 17.77$) early-type (concentration index $C \geq 2.8$) galaxies observed by both 2MASS and the second data release of SDSS (SDSS-DR2). All the sample galaxies have small magnitude uncertainties ($<0.15$ mag). Note that only galaxies with colour-fitted stellar ages smaller than 15 Gyr and stellar metallicities richer than 0.008 are selected for our sample galaxies. This is because the age of the Universe has been shown to be smaller than about 15 Gyr (e.g. Shafieloo et al. 2006) and the results for populations with metallicities poorer than 0.008 seems unreliable with large uncertainties. Then we use (r−K) and (u−r) colours to estimate the two stellar-population parameters of these galaxies, according to the results shown in Tables 2 and 3. The K-band magnitudes of galaxies are calculated from $K_s$-band magnitudes supplied by 2MASS, by using the same method as Bessell (2005). The k-corrections of $K_s$-band magnitudes are estimated as $-6 \log (1 + z)$, as used by Girardi et al. (2003), where z is the redshift. The galactic extinctions of K-band magnitudes are calculated using the model of Burstein & Heiles (1982). The u and z band magnitudes, and their k-corrections and galactic extinctions, are taken from the SDSS. The differences between SDSS magnitudes and AB magnitudes are taken into account, according to the values supplied by the SDSS. Fig. 2 shows the sample galaxies on the (u−r) versus (r−K) grid. For clarity, we have only plotted the error bars for the
Table 4. Stellar ages and metallicities of some old (age $\geq 4.6$ Gyr), young metal-rich (age $< 4.6$ Gyr and $Z \geq 0.02$) and young metal-poor (age $< 4.6$ Gyr and $Z < 0.02$) galaxies. The results are measured by two different methods (photometric and spectroscopic). The photometric results are determined using $(u-K)$ and $(z-K)$ colours in this work, and the spectroscopic results are obtained by Gallazzi et al. (2005). The symbol ‘objID’ is the unique SDSS identifier of each galaxy. Note that the definition of a metal-poor galaxy here is different from that in other parts of this paper, because of the limitation of our sample galaxies.

| Population type of galaxy | objID          | Age (Gyr) | Photometric results | Spectroscopic results |
|---------------------------|----------------|-----------|---------------------|-----------------------|
|                           |                |           | $Z$     | Error                        | $Z$     | Error                        |
| Old                       | 587727177921921120 | 4.6       | +3.6    | $0.0293$ | $+0.0140$ | $+0.0411$ | $+0.0077$ |
|                           | 587727225693143113 | 5.7       | +10.7   | $0.00300$ | $+0.0043$ | $+0.0291$ | $+0.0207$ |
|                           | 587727225692160083 | 9.1       | +5.4    | $0.0416$ | $+0.0082$ | $+0.029$ | $+0.0141$ |
| Young metal-rich          | 587727177921986670 | 2.7       | +0.6    | $0.0478$ | $+0.0022$ | $+0.0241$ | $+0.0220$ |
|                           | 587727225160466548 | 2.2       | +0.6    | $0.0385$ | $+0.0089$ | $+0.0301$ | $+0.0146$ |
|                           | 587727225689538771 | 2.7       | +0.5    | $0.0432$ | $+0.0068$ | $+0.030$ | $+0.0109$ |
| Young metal-poor          | 587727230524063879 | 3.7       | +8.0    | $0.0189$ | $+0.0128$ | $+0.0226$ | $+0.0087$ |
|                           | 587727227302707220 | 3.8       | +4.1    | $0.0166$ | $+0.0038$ | $+0.0251$ | $+0.0179$ |
|                           | 588848898845114541 | 2.9       | +2.7    | $0.0192$ | $+0.0097$ | $+0.025$ | $+0.0304$ |

Figure 3. Comparison of stellar ages and metallicities derived from colours with those from Lick indices. The results derived from colours are obtained in this work and those derived from Lick indices were obtained by Gallazzi et al. (2005). The typical errors of stellar ages obtained by colours and Lick indices are about 3.80 and 4.17 Gyr, respectively. The symbol ‘lick’ denotes the results of Gallazzi et al. (2005) while ‘colour’ denotes the results derived from $(r-K)$ and $(u-r)$. The suffix ‘corrected’ means the results corrected for the effects of YSPs. Dashed lines show a ± 3.5 Gyr spread about the unity (solid) line for stellar ages in (a) and (b) and show a ±0.015 spread in stellar metallicities in (c) and (d).

distributions of the uncorrected and corrected parameters in Fig. 4. We are shown that after the correction, the distributions of stellar ages obtained using the two methods, especially the peaks, become more similar after the correction (Fig. 4). However, it is also shown that the distributions of stellar metallicities obtained by various methods are similar. Therefore, it seems that without any correction, we can obtain correct distributions of stellar metallicities of luminous early-type galaxies via colours. Note that because we used a least-squares fitting method similar to Denicolò et al. (2005) and Li et al. (2006), the effects of the uncertainties of colours were not taken into account here. The uncertainties may affect the above distributions slightly. Furthermore, the dust may contribute to the difference between the two types of results. In fact, a small amount of dust can make the $(u-r)$ colours of galaxies redder, and then lead to additional
uncertainties in stellar ages. In detail, the dust of \( E(B-V) = 0.05 \) will change the \((u-r)\) and \((r-K)\) colours by about 0.12 mag, and then lead to an age uncertainty of about 2.5 Gyr and a metallicity uncertainty of 0.015. In addition, the average stellar-population parameters obtained by photometry and spectroscopy are found to be similar (about 7 Gyr for age and 0.02 for metallicity). Therefore, although it is difficult to obtain accurate stellar-population parameters of each galaxy using colours, we can obtain reliable values for the average age and metallicity of a sample of galaxies, as can the distributions of the two parameters.

5.2 Using colours in conjunction with spectroscopic indices

Because some colours are shown to be sensitive to stellar age or metallicity, we can possibly use colours in conjunction with Lick indices to study stellar-population parameters. For example, we can use a metallicity-sensitive colour together with an age-sensitive Lick index to estimate the stellar ages and metallicities of galaxies. We have attempted this in this work. The above galaxy sample is used here. The stellar-population parameters are fitted using H\(\beta\) and \((r-K)\) indices using the same method as in Section 5.1. The results are compared to those determined by Gallazzi et al. (2005) in Figs. 5(a) and (b). Note that the results were not corrected for the effects of YSPs. We see that when using H\(\beta\) instead of \((u-r)\), the stellar ages obtained are closer to those of Gallazzi et al. (2005). This means that line indices are affected more by young populations of galaxies. However, the fitted stellar metallicities of some galaxies are poorer than those obtained by Gallazzi et al. (2005). This should mainly be a result of the effects of YSPs in galaxies. In fact, YSPs make the \((r-K)\) colour of galaxies obviously bluer than those of the DSPs, but they affect the H\(\beta\) index more. When \((r-K)\) is used in conjunction with H\(\beta\) to estimate the stellar-population parameters of galaxies, the two indices lead to more poor metallicities compared those determined by a colour pair. Using an H\(\beta\) versus [MgFe] grid for comparison, the shape of the H\(\beta\) versus \((u-r)\) grid is similar to that of H\(\beta\) versus [MgFe]. Therefore, it is difficult to use photometry in conjunction with spectroscopy to estimate the metallicities of galaxies. Furthermore, we have tried to give some final results for the stellar-population parameters of our sample galaxies using the H\(\beta\), [MgFe], \((u-r)\) and \((r-K)\) indices together. Because the uncertainties of colours and Lick indices are different, we use a \(\chi^2\) fit (see, for example, Press et al. 1992) to estimate the stellar-population parameters. The stellar metallicities are shown to be significantly different from those determined by previous work. The comparison can be seen in Figs. 5(c) and (d). These results also were not corrected for the effects of YSPs. Because the results of Gallazzi et al. (2005) have taken the effects of YSPs into account, the above results are certainly affected by the YSPs in galaxies. The results may also be affected by the large observational uncertainties. However, it seems that the YSPs effect the results more, because when we tried to estimate the stellar-population parameters using H\(\beta\) and [MgFe], we obtained poorer metallicities than those of the previous work. As a whole, our results suggest it is more convenient to use colour pairs for estimating the stellar-population parameters of distant galaxies, as colours can be obtained more easily than spectra and can constrain the stellar-population parameters with uncertainties similar to Lick indices (typically 4 Gyr for age and 0.015 for metallicity).

6 DISCUSSION AND CONCLUSIONS

First, we investigated the relative metallicity sensitivities of AB system colours relating to \(u, B, g, V, r, I, z, J, H\) and \(K\) bands. Then, we studied the abilities of colour pairs for constraining luminosity-weighted stellar ages and metallicities. The results have shown that \([r-K], (u-R)\) and \([r-K], (u-r)\) are the best colour pairs for breaking the stellar age–metallicity degeneracy, while colour pairs such as \([R-K], (u-R)\), \([I-K], (u-R)\), \([R-K], (u-r)\) and \([I-J], (u-R)\) can also be used. Colour pairs \([r-K], (u-R)\) and \([r-K], (u-r)\) can measure two stellar-population parameters with small uncertainties (\(\Delta T < 3.89\) Gyr, \(\Delta[Z/H] < 0.34\) dex for typical uncertainties in colours). However, the age uncertainties for old populations (age \(\geq 4.6\) Gyr) and metal-poor populations (\(Z < 0.001\)) are always significantly larger than for young populations (age \(\leq 4.6\) Gyr) and metal-rich populations (\(Z \geq 0.001\)). This is because the colours of some old or metal-poor populations are largely indistinguishable within present typical errors. We can use Fig. 3 for comparison. However, the metallicity uncertainty of metal-poor populations (about 0.0024) is much less than that of other populations (about 0.015). In this work, we did not take into account the uncertainties in theoretical stellar-population models. For a detailed study of this, please refer to the work of Yi (2003). Furthermore, colours are usually affected by the dust of galaxies, even in early-type galaxies. A typical effect of dust in early-type galaxies, \(E(B-V) \sim 0.05\), will change the \((r-K)\) and \((u-r)\) colours of galaxies by about 0.12 mag, and then lead to additional uncertainties in stellar-population parameters (about 2.5 Gyr for age and 0.015 for metallicity). Thus, it is more suitable to use colours to measure the stellar-population parameters of galaxies with poor dust and gas, such as luminous early-type galaxies (with small colour uncertainties). Actually, a study to quantify the age and metallicity errors induced by typical dust is in progress. When we compare the results determined by photometry with those determined by Lick indices, we find that the stellar ages determined by colours are less than those determined by Lick indices. The difference mainly results from the effects of young populations in these galaxies. We also find that the average uncertainties of stellar-population parameters determined by colours and Lick indices are similar (typically 4 Gyr for age and 0.015 for metallicity). Therefore, it is actually difficult to obtain the absolute values.
Figure 5. Stellar-population parameters measured using colours in conjunction with line indices are plotted versus those measured by a few line indices. The suffix 'comp' represents the results derived from Hβ and (r–K) while 'all' denotes the results measured by two colours in conjunction with two line indices. Lines have meanings similar to Fig. 4. The typical uncertainties for stellar ages and metallicities are 4 Gyr and 0.015, respectively.

of stellar ages and metallicities using colours, but we can obtain some relative values. This will be useful for some statistical studies of the stellar populations of galaxies. In addition, our results suggest that, for estimating the two stellar-population parameters, it is better to use colours relating to both UBVRIJK and ugriz bands than to use those only relating to one of the two types of bands. According to the results, we can estimate the stellar-population parameters of some distant galaxies, using the photometry data supplied by, for example, the SDSS and 2MASS. The possible uncertainties of using various colour pairs can be estimated. The results presented in this paper can also help us to choose suitable bands for the observation of stellar-population studies.

We have also tried to find some colour pairs that are suitable for estimating the luminosity-weighted ages and metallicities of some special stellar populations. The results show that some colour pairs for estimating the two stellar-population parameters of young (age <4.6 Gyr), old (age ≥4.6 Gyr), metal-poor (Z < 0.001) and metal-rich (Z ≥ 0.001) populations are different. However, [(r–K), (u–r)] can be used to estimate the ages and metallicities of all stellar populations.

Although we used the BC03 model for our work, the results can be used for other models, as most stellar-population synthesis models predict similar colours for the same population. Furthermore, we suggest choosing a colour pair for estimating the two stellar-population parameters of galaxies, although a few colours can give a smaller range for the two parameters. This is because galaxies usually contain more than two populations, and by comparing observational colours with predictions of SSPs, we can only measure younger stellar ages and richer stellar metallicities for galaxies compared with the DSPs of galaxies. For a sample of galaxies, the effects of young populations on the ages and metallicities of DSPs can be roughly corrected, and some reliable estimations for the averages and distributions of two stellar-population parameters can be obtained (Li & Han 2007).

Note that the BC03 model is a single stellar-population model, which does not take into account binary interactions. This is actually different from the real stellar populations of galaxies. If stars of a population evolve as binaries rather than single stars, the colours of the population will be different from those of a single stellar population. Typically, the (u–r) and (r–K) colours predicted by binary stellar populations will be bluer by about 0.05 mag than those predicted by single populations. Using binary populations instead of single populations, the stellar ages and metallicities will be about 1.14 Gyr older and 0.0093 more metal-rich, respectively. A detailed study of this will be made in the future.

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