The effects of ultraviolet photometry and binary interactions on photometric redshift and galaxy morphology

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ABSTRACT
Using the HYPERZ code and a template spectral library, which consists of four observed galaxy spectra from Coleman, Wu & Weedman (CWW) and eight spectral families built with evolutionary population synthesis models, we present photometric redshift (photo-z) estimates for a spectroscopic sample of 6531 galaxies. Spectroscopic redshifts are also available, and are selected from the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7) and the Galaxy Evolution Explorer (GALEX) Data Release 4 (DR4). There are also morphologies for a morphological sample of 1502 bright galaxies, which are from the catalogue of Fukugita et al., and these are also matched with SDSS DR7 and GALEX DR4.

We find that the inclusion of $F_{\text{UV}}$ or $N_{\text{UV}}$, or both, decreases the number of catastrophic identifications ($|z_{\text{phot}} - z_{\text{spec}}| > 1.0$). If catastrophic identifications are removed, the inclusion of both $F_{\text{UV}}$ and $N_{\text{UV}}$ photometry mainly increases the number of non-catastrophic identifications in the low-redshift, $g-r \lesssim 0.8$ and fainter $r$-magnitude regions. The inclusion of binary interactions mainly increases the number of non-catastrophic identifications and decreases the deviations in the $0.3 \leq g-r \leq 0.8$ region when only using optical photometry.

Based on the morphological galaxy sample, we find that the inclusion of ultraviolet (UV) photometry decreases and increases the probability that early types are classified as burst and E types, respectively. This increases the probability that late types are classified as CWW-Sbc and CWW-Scd types. If catastrophic identifications are excluded, the inclusion of UV data mainly increases the identifications of late types in all redshift, bluer $g-r$ and $r \gtrsim 14$ regions. Moreover, binary interactions mainly affect the determinations of E and S0 types.

In comparison, we find that the reliability and completeness for early- and late-type selection by the HYPERZ code are less than those by the concentration index $C = 2.6$, the profile likelihood $P_{\exp} - P_{\text{de V}} = 0$ and colour $u-r = 2.22$ criteria. Moreover, we find that $N_{\text{UV}} - u = 1.94$ and $5.77 - 1.47(u-r) = F_{\text{UV}} - u$ discriminators can be used as morphology selection indicators. These two criteria have comparable reliability and completeness for selecting early- and late-type galaxies to $C = 2.6$ criterion and higher completeness for early-type selection than the $u-r = 2.22$ criterion.

Key words: binaries: general – galaxies: distances and redshifts – galaxies: fundamental parameters – ultraviolet: galaxies.

1 INTRODUCTION
The redshift is one of the key components of cosmology. It can be used to estimate distances, and thus to place observed properties on a physical scale. Many modern astrophysical measurements and studies (the identification of galaxy clusters and very high redshift objects, baryon acoustic oscillation measurements, galaxy evolution, large-scale structure and gravitational lensing research) have benefited from substantially larger catalogues of redshifts (Gerdes et al. 2010).

The galaxy redshift plays an important role in studies of galaxy formation and evolution. The spectroscopic redshifts of many relatively bright galaxies have already been obtained. However, those of fainter galaxies are difficult to obtain. The redshifts of fainter galaxies ($R \gtrsim 25$ mag), as well as upcoming surveys, will exclusively rely on broad-band, medium-band or custom-designed narrow-band photometry, because this photometry is $\sim 2$ orders of magnitude...
less time-consuming than the spectroscopy for a given telescope size (Brammer, van Dokkum & Coppi 2008; Niemack et al. 2009, and references therein).

The technique for deriving redshifts from broad-band photometry was pioneered by Baum (1962). So far, a number of codes have been developed to compute photometric redshifts (photo-z), such as Bpz (Benítez 2000), HYPERZ (Bolzonella, Miralles & Pello 2000), greggzz (Rudnick et al. 2001, 2003), IMPPZ (Baddedge et al. 2004), LE PHARE (Arnouts & Ilbert, 2000), ZEBRA (Feldmann et al. 2006), KCORRECT (Blanton & Roweis 2007), LRT (Assef et al. 2008), easyZ (Brammer et al. 2008), ARBorz (Gerdes et al. 2010), artificial neural networks (ANNs), and so on. Three types of algorithm have been used in the photo-z calculations (Abdalla et al. 2008; Brammer, van Dokkum & Coppi 2008; Gerdes et al. 2010; Niemack et al. 2009; Zhang, Li & Zhao 2009).

(i) The template-fitting approach: in this scheme, photo-z is obtained by comparing the observed spectra with a set of template spectra, which can be based on either population synthesis models or empirical studies.

(ii) The empirical training set approach: the basic principle of this method is the derivation of a parametrization of redshift through the magnitudes of the galaxies in a training set. This parametrization is then applied to galaxies whose redshifts need to be estimated, yielding an estimation of the photometric redshift. The galaxies in the training set have known spectroscopic redshifts and similar properties to the galaxies for which one wants to estimate the redshifts. The ANN is an empirical training set approach.

(iii) The instance-based learning method: this method also relies on the real data.

Among the traditional template-fitting codes, some of these (such as HYPERZ, IMPPZ, LE PHARE, etc.) use a straightforward $\chi^2$ minimization algorithm to obtain the photo-z. As the spectral information provided by broad-band photometry is at low resolution, the photo-z of galaxies have relatively large errors. To avoid catastrophic errors, some codes have improved the template spectra. For example, Niemack et al. (2009) developed a set of high-resolution spectral templates based on the galaxy physical information about the star-formation history. Other codes have used a refinement of the $\chi^2$ minimization method: (i) the Bpz code incorporated Bayesian statistics and allowed the use of extra information on galaxies (priors); (ii) the easyZ, ZEBRA and KCORRECT codes used the hybrid method. The easyZ code allows the linear combination of templates, as in the greggzz code, and the use of priors. The ZEBRA code uses a combination of priors (which are used to calculate a prior self-consistently from the photometric catalogue when it is run in Bayesian mode) with the training set method (which is used to improve the standard set of templates in specified redshift bins in its template optimization mode with the advantage of the zCOSMOS data base; Lilly et al. 2007). The KCORRECT code uses the data of the Sloan Digital Sky Survey (SDSS; York et al. 2000) and incorporates the principle component analysis method to optimize the template. The priors of the luminosity function (Mobasher et al. 2007) and surface luminosity (Xia et al. 2009) are used in these photo-z codes.

Some of the non-traditional photometry fitting codes include the structural properties of galaxies. For example, Wray & Gunn (2008) used the surface brightness and the Sérsic index (a measurement of the radial light profile) in addition to five-band photometry to obtain photo-zs. Sarajedini et al. (1999) used the bulge-to-total flux ratio along with the /$F$ magnitude and V–$I$ colour to obtain photo-zs. Negrello et al. (2009) incorporated the features of polycyclic aromatic hydrocarbons and silicate features into the mid-infrared wavelength window to recover the photo-zs of starburst galaxies. Moreover, Kurtz et al. (2007, $\mu$-photoZ) only used one colour and the surface brightness from a single band to obtain the photo-zs of galaxies.

Now, photo-zs are extensively used in many studies; for example, they have been used in deep cosmological surveys to yield the galaxy luminosity function and the evolution of the star formation rate (SFR; Mobasher et al. 2007, and references therein).

Morphology is another important parameter for galaxies. First, it can be used to segregate galaxy clusters. Different morphological types exhibit distinctly different astrophysical properties, reflecting the different histories of the formation and evolution of galaxies (Shimasaku et al. 2001).

(i) The automated classification approach uses the parameter(s) sensitive to morphology to obtain automatically the galaxy morphology. This method takes less time, but faces a serious problem in that it is difficult to find such parameter(s). In the past, the following parameters have been used in the automated classification method: u–r colour (Strateva et al. 2001), profile probabilities (the relation between exponential $P_{ex}$ and de Vaucouleurs $P_{d V}$ profile likelihoods), concentration index (the ratio of the radii containing 90 to 50 per cent of the Petrosian r galaxy light, $C = r_{90}/r_{50}$; Shimasaku et al. 2001; Strateva et al. 2001), and so on.

(ii) The visual classification approach classifies galaxies using the visual inspection of experts or volunteers. This method serves as the most reliable method when adopting the Hubble classification (Sandage 1961) for galaxies with large apparent sizes (Shimasaku et al. 2001). The greatest disadvantages of this method are that it is more time-consuming, the size of the galaxy sample is small and the galaxies inspected are relatively bright. Fukugita et al. (2007) have compiled a catalogue of the morphological classifications of ~2500 bright galaxies in the SDSS Data Release 3 (DR3) using the visual inspection of three expert classifiers. The Galaxy Zoo project has invited a large number of volunteers to separate early-type galaxies from spirals in large data sets by using proxies for morphology (Lintott et al. 2008).

(iii) The spectrum fitting approach fits the observed spectra to the template spectra of galaxies with known morphological types.

(iv) The k-means method has also been used (Zhang et al. 2009).

We use one of the widely adopted template-fitting codes, HYPERZ, to obtain the photo-zs of galaxies. Meanwhile, the rough morphological types are also obtained because the HYPERZ code allows us to obtain the best set of fit parameters. As the first step of this work, we use the HYPERZ code to obtain the photo-zs and morphological types of galaxies with known spectroscopic redshifts and morphological

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1 Because Greg Rudnick did not name his code, we follow the nomenclature of Brammer et al. (2008).
2 See [http://www.oamp.fr/people/arnouts/LE_PHARE.html](http://www.oamp.fr/people/arnouts/LE_PHARE.html).
types. Thus, we can explore the ability of the HYPERZ code to recover the redshifts and morphological types of galaxies. We can also judge whether (and how) the recovered parameters are affected by the input parameters, including ultraviolet (UV) photometry, binary interactions and population synthesis models.

The reasons for discussing the influence of UV photometry and binary interactions on the determinations of photo-zs and morphological types are as follows.

(i) In previous works using the template-fitting method to obtain the photo-zs of galaxies, the template spectra usually come from real objects or population synthesis models of single stellar populations (SSPs), rather than the population synthesis models including binary interactions. As for the population synthesis models of binary stellar populations (BSPs), the Yunnan group (Zhang et al. 2004a, 2005) have considered various binary interactions in evolutionary population synthesis (EPS) models. They have concluded that the inclusion of binary interactions can affect the overall shape of the spectral energy distribution (SED) of the population. In particular, the SED of the population in the UV passbands is bluer by 2–3 mag at \( t \approx 1 \) Gyr if binary interactions are taken into account. The above conclusion has further been confirmed by Han, Podsiadlowski \& Lysias-Gray (2007, hereafter HPL07), who included hot subdwarf B stars (sdBs) in the population. The bluer SED in the UV passbands can be explained by the fact that binary interactions can create some important classes of objects, such as sdBs, for a population older than \( \sim 1 \) Gyr (HPL07) and blue stragglers at 0.5–1.5 Gyr.

(ii) Observations show that almost all elliptical galaxies have a UV-upturn phenomenon, that is, the flux increases with the wavelength decreasing from 2000 to 1200 Å (HPL07). This phenomenon can be explained by the EPS models of BSPs (HPL07). Thus, if only optical photometry and/or the EPS models of SSPs are used to obtain photo-zs and morphologies of elliptical galaxies, the question is whether these results are reasonable or not.

(iii) The photo-zs, which are derived by using the HYPERZ code neglecting UV photometry, significantly deviate from the spectroscopic redshifts for some galaxies in the redshift range \( z < 0.2 \).

In this paper, we use two samples of galaxies: spectroscopic and morphological. The galaxies in the spectroscopic sample are selected randomly from the SDSS DR7 and their spectroscopic redshifts are available. The galaxies in the morphological sample are from the catalogue of Fukugita et al. (2007), which presents the morphological types of 2253 bright galaxies in the SDSS DR3 using an independent classification scheme (visual classification). All galaxies in both samples have been matched with the Galaxy Evolution Explorer (GALEX) DR4 (see Section 3 for details). Moreover, we not only use the population synthesis models of SSPs but also those of BSPs to construct a theoretical template library (see Section 2). Niemack et al. (2009) have used the SDSS and GALEX photometric data to study the redshifts of galaxies, but they have used the population synthesis models of SSPs.

The outline of the paper is as follows. In Sections 2 and 3 we describe the method used to obtain the photo-z and the galaxy samples, respectively. In Sections 4 and 5, we obtain photo-z estimates for the spectroscopic galaxy sample and morphologies for the morphological galaxy sample. We discuss the effects of UV photometry and binary interactions on these. Finally, we present a summary and conclusions in Section 6.

2 METHOD

The photo-z and galaxy morphology are computed through the HYPERZ code of Bolzonella et al. (2000). This is the first publicly available photo-z code and has been widely used in the literature for photo-z estimations of galaxies (Abdalla et al. 2008). HYPERZ is a template-fitting procedure and adopts a standard \( \chi^2 \) minimization algorithm:

\[
\chi^2 = \sum_{i=1}^{N_{\text{spec}}} \left( \frac{F_{\text{obs},i} - b F_{\text{temp},i}}{\sigma_i} \right)^2.
\]

Here, \( F_{\text{obs},i} \) and \( F_{\text{temp},i} \) are the observed and template fluxes and \( \sigma_i \) are the observed and template fluxes and their uncertainty in filter \( i \), respectively, and \( b \) is a normalization constant.

The HYPERZ code is based on the fit of the overall shape of the spectra and on the detection of strong spectral features, such as the 4000-Å break, Balmer break, Lyman decrement or strong emission lines. It adopts a standard SED fitting method. HYPERZ takes as its inputs the filter set and the photometric catalogue of galaxies, which comprises magnitudes and photometric errors through the filters specified in the filter set. For a given filter set and galaxy catalogue, the relevant parameters introduced in the photo-z calculation are: (i) the set of template spectra, which can be observed SEDs or built with spectral models or both (see this section), and if spectral models are used, the type of SFR, the possible link between the age and the metallicity of the stellar population and the choice of an initial mass function (IMF) are involved; (ii) the reddening law (HYPERZ provides five laws to choose from); (iii) flux decrements in the Lyman forest; (iv) the limiting magnitude in each filter; (v) the cosmological parameters \( H_0, \Omega_M \) and \( \Omega_L \), and so on.

Descriptions of the filter set and the photometric catalogue of galaxies are presented in Section 3. In this section we describe emphatically the template spectral library (Sections 2.1 and 2.2) and the definition of models (see Section 2.3).

2.1 Spectral synthesis models

In the HYPERZ package, the observed SEDs and the spectral synthesis models of the Galaxy Isochrone Synthesis Spectral Evolution Library (GISSEL98; Bruzual \& Charlot 1993) are provided. To check the effects of spectral synthesis models and binary interactions on the determinations of photo-zs and morphologies of galaxies, we also build theoretical SEDs using the Bruzual \& Charlot (2003, hereafter BC03), HPL07 and Yunnan models (Zhang et al. 2002, 2004a,b, 2005).

The GISSEL98 and BC03 models were built by Bruzual \& Charlot in 1993 and 2003, respectively. In this work, we use the GISSEL98 models with the IMF by Miller \& Scalo (1979) and the BC03 models, which use the Padova 1994 stellar evolutionary tracks and the Chabrier (2003) IMF, because the choice of IMF has a negligible impact on the final results (Bolzonella et al. 2000). Neither model takes binary interactions into account.

The HPL07 models include the binary interactions of sdBs (Han et al. 2002, 2003) in populations. The Yunnan models have been developed by Zhang and her colleagues. In their models, the rapid single/binary evolution codes (Hurley, Pols \& Tout 2000; Hurley, Tout \& Pols 2002) are used for single/binary evolutionary tracks (the rapid binary evolution code includes those binary interactions studied before 2002). Both models present the SEDs of populations
2.2 Theoretical template SED library

The template spectral library should comprise SEDs with different ages and spectral types of galaxies. Spectral synthesis models only provide the SEDs of populations without any SFR at different ages. Therefore, at a given age we need to generate the SEDs of galaxies with different galaxy types by means of spectral synthesis models. In this study, we include elliptical (E), lenticular (S0), spiral (from Sa to Sd) and irregular (Irr) types.

Studies have found that the observed properties of local field galaxies with different galaxy types can be roughly matched by a population with different SFRs. Therefore, using the BC03 software package we have built eight SFRs (corresponding to the types from E to Irr): a delta burst, a constant star-formation system, and six $\mu$-models with characteristc time decoays (exponentially decreasing SFR, $\tau = 1, 2, 3, 5, 10, 15$ and $30$ Gyr; see equation 2) chosen to match the sequence of colours from E–S0 to Sd (Bolzonella et al. 2000):

$$\psi(t) = [1 + \varepsilon M_{\text{PG}}(t)]^{-1} \exp(-t/\tau).$$

Here, $\tau$ is the e-folding time-scale, $M_{\text{PG}}(t) = [1 - \exp(-t/\tau)] - M_{\text{stars}} - M_{\text{remnants}}$ is the mass of gas that has been processed into stars and then returned to the interstellar medium (ISM) as a result of stellar evolution at time $t$, $M_{\text{stars}}$ and $M_{\text{remnants}}$ are the masses of stars and remnants at $t$, and $\varepsilon$ denotes the fraction of $M_{\text{PG}}(t)$ that can be recycled into new star formation.

By convolving these eight SFRs with the SEDs of the populations, we generate eight spectral families for the given spectral synthesis models. Each family (corresponding to a certain SFR) includes the SEDs at different ages.

In this study, the number of ages (221; see Table 1) is reduced to 51 for each spectral family built with the GISSEL98 and BC03 models (refer to Bolzonella et al. 2000 for details), while it remains unchanged for the family built with the HPL07 and Yunnan models. This is because the HYPERZ code does not interpolate on the template grids and the template set must be densely populated (Maraston 2005).

2.3 Definition of models

The observed spectra, provided by the HYPERZ package, include four mean spectra of local E-, Sbc-, Scd- and Irr-type galaxies from Coleman, Wu & Weedman (1980, hereafter CWW), which we refer to as CWW-E, CWW-Sbc, CWW-Scd and CWW-Irr, respectively. These spectra extend from 1400 to 10 000 Å originally and have been extended to the UV and near-infrared regions by means of GISSEL98 spectra with parameters (SFR and age) selected to match the observed spectra at $z = 0$ (Bolzonella et al. 2000).

In all of the following computations, the template SED library is constituted by eight theoretical spectral families (corresponding to

Table 1. Description of GISSEL98, BC03, HPL07 and Yunnan spectral synthesis models.

| Population | GISSEL98 and BC03 (SSP and BSP) | HPL07 (SSP) | Yunnan (SSP and BSP) |
|------------|---------------------------------|-------------|---------------------|
| Ages       | 221                             | 88          | 90                  |
| $\log(t_f \text{ yr}^{-1})$ | 5.100                            | 8.000       | 5.000               |
| $\log(t_i \text{ yr}^{-1})$ | 10.300                           | 10.175      | 10.175              |
| $\Delta \log(t \text{ yr}^{-1})$ | 0.050 [5.100 $\leq \log(t \text{ yr}^{-1}) < 6.000; 7.757 \leq \log(t \text{ yr}^{-1}) < 9.207$] | 0.025       | 0.100 [5.000 $\leq \log(t \text{ yr}^{-1}) < 6.500$] |
|           | 0.020 [6.000 $\leq \log(t \text{ yr}^{-1}) < 7.440$] |             | 0.050 [log(t yr$^{-1}$) $\geq 6.500$] |
|           | 0.005~0.038 [7.440 $\leq \log(t \text{ yr}^{-1}) \leq 7.757; \log(t \text{ yr}^{-1}) \geq 9.207$] |             |                     |

Figure 1. Comparison of SEDs for the BC03 (red dotted line), Yunnan (black solid line + triangles for Yunnan-b; black solid line for Yunnan-s) and HPL07 (green dot-dashed line + circles for HPL07-b; green dot-dashed line for HPL07-s) models for a solar-metallicity population (normalized to 1 $M_{\odot}$) at log(t) = 8.85 yr.

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burst, E, S0–Sd and Irr types), generated by spectral synthesis models, and four observed galaxy spectra from CWW. For the sake of clarity, six models are defined. Each model differs from the others by changing the set of theoretical template SEDs (eight spectral families) in the HYPERZ code. Models A/B/C/D use the theoretical template SEDs, which were built with the GISSEL98/BC03/HPL07s/Yunnan-s models (i.e. the models for SSPs), respectively; models C2/D2 use those with the HPL07-b/Yunnan-b models (i.e. the models for BSPs). All the other relevant parameters introduced in the computations are fixed, except for the set of filters and the catalogue of galaxies. The description of parameters adopted by us is as follows.

(i) The combination of the CWW set of empirical SEDs with the theoretical template spectra is used because the CWW set produces slightly better results than GISSEL98 (because of a Lyman blanketing effect) in the high-redshift domain. Also, GISSEL98 models produce more accurate results than the CWW templates alone in the low-redshift domain. All eight theoretical spectral families are used, although there is no obvious gain when the set of five SFRs (one delta burst, three $\mu$-decaying and one constant star-formation system; Bolzonella et al. 2000) is used. Moreover, during the construction of the theoretical template SEDs:

(1) we assume that the gas is not recycled into new star formation once it has been processed into stars (i.e. $\epsilon = 0$; see equation 2);
(2) we neglect the attenuation by dust;
(3) we only use solar-metallicity EPS models because Bolzonella et al. (2000) have found that there is only a slight improvement of the accuracy of photo-$z$ at $z \leq 1.5$ when several different metallicities are used together (they found that including different metallicities does not affect the high-redshift determinations);
(4) we only use a certain IMF for each set of EPS models because the photo-$z$ estimates are approximately the same, whatever the IMF used (Bolzonella et al. 2000).

(ii) The reddening law of Calzetti et al. (2000) is used to deredden the data because most of the fits to the galaxies from the Hubble Deep Field (HDF) using the Calzetti reddening law produce better $\chi^2$ values than when using the other attenuation laws provided by the HYPERZ package (Bolzonella et al. 2000). In addition, in the computations $A_V \equiv R_V(E(B-V))$ ranges from 0.0 to 1.2 in steps of 0.2.

(iii) The default values of flux decrements in the Lyman forest are used, although their variation can affect the determination of photo-$z$, for example, decreasing them can induce an overestimate of photo-$z$.

(iv) In the case of non-detection in filter $i$ (characterized by the $i$-passband magnitude $m(i) = 99$ in the catalogue of galaxies), the contribution of the $i$th filter is also taken into account in the $\chi^2$ calculation by assuming the flux in the $i$–passband is 0 and the flux error equals that deduced from the limiting magnitude ($\Delta F_{obs} = \Delta F_{lim}$). This assumption is the usual setting when dealing with a relatively deep survey in the considered filter (Bolzonella et al. 2000). The limiting magnitudes in the $F_{NUV}$ and $F_{NUV,ugriz}$ passbands are set to 29, 29, 30, 30, 30 and 30 mag, respectively.

(v) The minimum of the photometric error $\Delta m_{min}$ is set to 0.05 because there is no significant gain for $\Delta m_{min}$ $\leq$ 0.05 (about 5 per cent accuracy; Bolzonella et al. 2000). When the input error from the catalogue is less than this value, $\Delta m_{min}$ replaces the input error to avoid too small and non-photometric errors.

(vi) The set of cosmological parameters ($\Omega_M, \Omega_X, H_0$) = (0.3, 0.7, 70) is used. The variation in this set of parameters from (1.0, 0.0, 50) to (0.3, 0.7, 50) only affects $\delta_i$ by less than 1 per cent (Bolzonella et al. 2000). Here, $H_0$ is in units of km s$^{-1}$ Mpc$^{-1}$, $\delta_i \equiv \sigma/(1 + (z))$ and $\sigma = \sqrt{\sum_i [z_{ob,i} - z_{spec,i}]/(N - 1)}$.

(vii) The redshift ranges from 0 to 7 in steps of 0.02 instead of 0.05 (default value) although the primary $z$-step between 0.1 and 0.05 does not significantly affect the results (Bolzonella et al. 2000).

### 3 GALAXY SAMPLE

To check the ability of recovering photo-$z$s and morphological types of galaxies, we need to collect the galaxies with known spectroscopic redshifts and morphological classifications, and the redshift coverage of galaxies should be as wide as possible. However, because of limited observations, the galaxies with known classifications are relatively bright and their redshifts are low. Two galaxy samples (called spectroscopic and morphological) are used in this work, and they are used to study the ability to recover photo-$z$s and galaxy types, respectively.

The galaxies in the spectroscopic sample are selected from the SDSS DR7. In order to ensure that the selected objects can be used in the studies of Section 4, we use the following criteria. The spectroscopic redshifts must be available (from SDSS.SpecObj), and GALAXY must be defined as the object class by all of the following three methods: spectral classification (SDSS.SpecObj.specClass=2), piPlugMap type (SDSS.SpecObj.objType=0) and morphological classification (SDSS.Galaxy.type=3). Initially, we obtain a sample of 773 126 galaxies from the SDSS DR7. To save computational time, we use one-seventieth of this galaxy sample as the primitive spectroscopic sample. This totally comprises 11 043 galaxies, which are randomly selected.

The galaxies in the morphological sample are 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. The morphological classification in the catalogue of Fukugita et al. (2007) is obtained by visual inspection of images in the $g$ band. Removing the objects mismatched with the SDSS DR7 (the matching radius is 6 arcsec) produces an initial morphological sample of 1792 galaxies. Note that the redshifts of galaxies in this catalogue are low (less than 0.2).

### 3.1 Matching the SDSS DR7 sample with GALEX DR4

We adopt the method of Agueros et al. (2005) and Obric et al. (2006) to match SDSS DR7 and GALEX DR4. The matching radius between SDSS DR7 and GALEX DR4 is 6.0 arcsec and the nearest neighbour is taken as a true associate if its distance is smaller than the matching radius. When the nearest object has no simultaneous $F_{NUV}$ and $N_{UV}$ detections, the nearer object (within the matching radius) with simultaneous $F_{NUV}$ and $N_{UV}$ detections will be taken as its associate (361 galaxies for spectroscopic sample). If no object within the matching radius has simultaneous $F_{NUV}$ and $N_{UV}$ detections, the missing magnitude of the nearest object will be replaced by the corresponding magnitude of the nearer objects (within the matching radius).

Finally, we obtain a final spectroscopic sample of 6531 galaxies. Fig. 2 gives the spatial distribution of these matched (i.e. spectroscopic sample) and mismatched galaxies in the primitive spectroscopic sample. From this, we see that the galaxies in the spectroscopic sample are indeed randomly distributed. Also, we obtain a final morphological sample of 1502 galaxies. The
spectroscopic and morphological galaxy samples are used in the studies of Sections 4 and 5, respectively.

SDSS DR7 provides the values of various magnitudes (such as devMag, expMag, modelMag, petroMag, psfMag, etc). We choose SDSS modelMag (exactly, the shorthand alias for modelMag) of galaxies as the SDSS C-model magnitude (based on de Vaucouleurs and exponential fitting) is an adequate proxy to use as a universal magnitude for all types of objects. It has an excellent agreement with the Petrosian magnitude for galaxies. Moreover, the SDSS C-model magnitude is a reliable estimate of galaxy flux and can account for the effects of local seeing. Thus, it is less dependent on local seeing variations (http://www.sdss.org/DR7/algorithms/photometry.html).

### 3.2 Filters

The filters involved in the computations include those equipped in the SDSS system and those in the GALEX system. The transmission curves ($S_\lambda$) of these filters are presented in Fig. 3. The data about the SDSS filters for a null airmass ($ugriz_0$) are from the BC03 package.

| Filters | $\lambda_{\text{eff}}$ (Å) | Width (Å) |
|---------|-----------------|----------|
| $F_{\text{UV}}$ | 1539.781 | 252.031 |
| $N_{\text{UV}}$ | 2313.893 | 729.648 |
| $u_0$ | 3523.768 | 587.708 |
| $g_0$ | 4798.005 | 1327.291 |
| $r_0$ | 6258.645 | 1333.650 |
| $i_0$ | 7655.315 | 1345.910 |
| $z_0$ | 8984.980 | 1193.529 |

In the left panels of Figs 4–6, we give comparisons between SDSS spectroscopic ($z_{\text{spec}}$) and photometric ($z_{V_{\text{phot}}}$) redshifts for models A–D2 (see Section 2.3). From these, we see that for most of the galaxies ($\sim 71.3$ per cent for model C) $z_{V_{\text{phot}}}$ is less than 1.0 and the difference between spectroscopic and photometric redshifts $|\Delta z_{V}| (\equiv |z_{\text{spec}} - z_{V_{\text{phot}}}|)$ is less than 0.2. For some of the galaxies ($\sim 27.4$ per cent for model C) $z_{V_{\text{phot}}}$ ranges from 1.8 to 2.8 but $z_{\text{spec}}$ is less than 0.2 (these galaxies are located within the box shown in the left panels of Figs 4–6).

In the right panels of Figs 4–6, we give comparisons between $z_{\text{spec}}$ and $z_{V_{\text{phot}}}$ for models A–D2. By comparing with the

### 4 ULTRAVIOLET PHOTOMETRY, BINARY INTERACTIONS AND POPULATION SYNTHESIS MODELS ON PHOTO-z DETERMINATIONS

In this section, we use the HYPERZ code to obtain photo-z estimates of galaxies in the spectroscopic sample. We discuss the effects of UV photometry, binary interactions and population synthesis models on photo-z determinations.

All the parameters we have adopted in the HYPERZ procedure (including the set of template spectra, the reddening law, etc.), have already been described in Section 2.3. In Appendix A, we present the influence of these parameters on photo-z estimates of galaxies in the spectroscopic sample.

#### 4.1 Ultraviolet photometry on photo-z determinations

##### 4.1.1 Effect of ultraviolet photometry

We obtain photo-z estimates ($z_{V_{\text{phot}}}$) of galaxies in the spectroscopic sample by only using SDSS ugriz data and photo-z estimates ($z_{V_{\text{phot}}}$) by using the full set of $F_{\text{UV}}, N_{\text{UV}}, ugriz$ photometry for models A–D2 (see Section 2.3).

In the left panels of Figs 4–6, we give comparisons between SDSS spectroscopic ($z_{\text{spec}}$) and photometric ($z_{V_{\text{phot}}}$) redshifts for models A–D2, respectively. From these, we see that for most of the galaxies ($\sim 71.3$ per cent for model C) $z_{V_{\text{phot}}}$ is less than 1.0 and the difference between spectroscopic and photometric redshifts $|\Delta z_{V}| (\equiv |z_{\text{spec}} - z_{V_{\text{phot}}}|)$ is less than 0.2. For some of the galaxies ($\sim 27.4$ per cent for model C) $z_{V_{\text{phot}}}$ ranges from 1.8 to 2.8 but $z_{\text{spec}}$ is less than 0.2 (these galaxies are located within the box shown in the left panels of Figs 4–6).

In the right panels of Figs 4–6, we give comparisons between $z_{\text{spec}}$ and $z_{V_{\text{phot}}}$ for models A–D2. By comparing with the
Effects of UV photometry on photo-z

Figure 4. Comparisons between spectroscopic ($z_{\text{spec}}$) and photometric ($z_{\text{phot}}$) redshifts for the spectroscopic galaxy sample (see Section 3.2). The left panels are when only using optical ($ugriz$) photometry. The right panels are when using the combination of UV with optical photometry ($F_{\text{UV}}N_{\text{ugriz}}$). The top and bottom panels are for models A and B, respectively. In each panel, dot-dashed, dashed and solid lines correspond to $|\Delta z| = 0.2, 0.5$ and $1.0$. Dots and crosses denote galaxies with $z_{\text{phot}} \leq 1.0$ and $z_{\text{phot}} > 1.0$. Red, black, green and purple symbols denote galaxies with the photo-z probability $P(\chi^2) > 99$, $99 \geq P(\chi^2) > 90$, $90 \geq P(\chi^2) > 68$ and $P(\chi^2) \leq 68$ (see equation 1), respectively.

Figure 5. Similar to Fig. 4, but for models C and C2 (top and bottom panels, respectively).

corresponding left-hand panels, we find that the number of galaxies with $z_{\text{UV}}^{\text{Vphot}} < 1.0$ and $|\Delta z_{\text{UV}}^{\text{Vphot}}| < 0.2$ is largely increased ($\sim 98.0$ per cent for model C). The number of galaxies with $1.8 \leq z_{\text{UV}}^{\text{Vphot}} \leq 2.8$ and $z_{\text{spec}} \leq 0.2$ is significantly decreased ($\sim 0.18$ per cent for model C). That is to say, the inclusion of UV photometry makes a difference; the photometric and spectroscopic redshifts ($|\Delta z|$) are smaller (from 1.8–2.8 to less than 0.2) for these galaxies. We must be cautious when we only use optical data to obtain the photo-z estimates of these galaxies. What are the characteristics of these galaxies?

4.1.2 Which galaxies are affected?

According to the results about $z_{\text{Vphot}}^{\text{Vphot}}$ and $z_{\text{UV}}^{\text{Vphot}}$, we divide the spectroscopic galaxy sample into four subsamples for each model. The galaxies in the four subsamples respectively satisfy the following conditions:

(i) both $z_{\text{Vphot}}^{\text{Vphot}}$ and $z_{\text{UV}}^{\text{Vphot}}$ are less than 1.0, and the differences, $|\Delta z_{\text{V}}|$ and $|\Delta z_{\text{UV}}^{\text{Vphot}}|$, are less than 0.2;  
(ii) $z_{\text{Vphot}}^{\text{Vphot}} \geq 1.0$ and $z_{\text{UV}}^{\text{Vphot}} \leq 1.0$;  
(iii) both $z_{\text{Vphot}}^{\text{Vphot}}$ and $z_{\text{UV}}^{\text{Vphot}}$ are greater than 1.0;  
(iv) $z_{\text{Vphot}}^{\text{Vphot}} \leq 1.0$ and $z_{\text{UV}}^{\text{Vphot}} \geq 1.0$.

This division means that the photo-z estimates of galaxies in the first subsample can be obtained reasonably when only using optical $ugriz$ data. The photo-z errors of galaxies in the second subsample can be decreased by the combination of UV with optical data. The photo-z estimates of galaxies in the third subsample cannot be obtained reasonably even if UV data are combined. The photo-z estimates of galaxies in the fourth subsample are erroneously identified if UV photometry is included. Fig. 7 gives a comparison between $z_{\text{Vphot}}^{\text{Vphot}}$ and $z_{\text{UV}}^{\text{Vphot}}$ for model A. The galaxies in the four subsamples occupy the lower-left (except 80 galaxies for which $0.2 < |\Delta z| < 0.5$), upper-left, upper-right and lower-right regions, respectively.
To investigate the properties of the galaxies in each subsample, according to the results of model A, in Fig. 8 we present the distribution of galaxies in the diagrams of \( \chi^2_{\text{phot}} \) versus \((g'-r')_\text{spec}, (g'-r')_\text{phot}\) versus \((g'-r')\), \((N_{uv}-u')\) versus \((g'-r')\) and \((u'-r')\) versus \((g'-r')\). In Fig. 9 we present the magnitude \( (F_{UV}^\text{N}, N_{uv}, u', g', r', i' \text{ and } z') \) distribution of galaxies along the wavelength. In Fig. 10 we give the photo-z probability \( P(\chi^2) \) as a function of redshift for an arbitrary galaxy in the second, third and fourth subsamples when using \( ugriz \) and \( F_{UV} N_{uv} ugriz \) photometry. In each panel of Fig. 10, the magnitudes and magnitude errors of the corresponding galaxy are also shown. Note that all of these magnitudes are corrected for foreground extinction using the Schlegel et al. (1998) reddening maps, the extinction law of Schlegel et al. (1998) for SDSS \( ugriz \) magnitudes and that of Cardelli, Clayton & Mathis (1989, hereafter CCM) for \( GALEX F_{UV} \) and \( N_{uv} \) magnitudes. By averaging the CCM extinction law over \( GALEX F_{UV} \) and \( N_{uv} \) bandwidths, Wyder et al. (2005) obtained \( A_{g}/E(B-V) = 8.374 \) and \( A_{N_{uv}}/E(B-V) = 8.741 \) (Donas et al. 2007). Meanwhile, all of these magnitudes are \( k \)-corrected using the SDSS spectroscopic redshift \( z_{\text{spec}} \) and the \( K \)-correction \( v4.1.A \) code of Blanton & Roweis (2007), in which the distance moduli are obtained by assuming the cosmological parameters \( (\Omega_m, \Omega_{\Lambda}) = (0.3, 0.7) \).

(i) From Fig. 8, we see that the galaxies in the first and second subsamples are redder \((g'-r' \geq 0.70)\) and bluer \((g'-r' \leq 0.70)\), respectively. The main reason that the photo-zs of galaxies in the second subsample are erroneously identified using optical photometry is that bluer galaxies are often accompanied by star formation (Rich et al. 2005). This leads to a probability function \( P(\chi^2) \) with a significant secondary peak in the photo-z calculation (see the left panel of Fig. 10). The secondary peak (in the region \( 1.8 \lesssim z \lesssim 2.8 \)) is explained by the fact that the 4000-Å break, which is the most commonly used spectral feature for optical photo-z determination, is greatly reduced (making it more difficult to use as a redshift indicator; Niemack et al. 2009, and references therein). Also, in the \( 1.8 \lesssim z \lesssim 2.8 \) region, the 4000-Å break goes beyond the wavelength coverage of \( ugriz \) filters (making it impossible to use as a redshift indicator). When UV data are combined, the Lyman break, which is exhibited by all galaxies, would emerge in the UV ranges if \( 1.8 \lesssim z \lesssim 2.8 \). This would largely decrease the probability of the solution in the high-redshift domain.

(ii) The third spectroscopic subsample (including 30 galaxies) constitutes nine galaxies with the full set of photometry and 21 galaxies with \( N_{uv} ugriz \) detections (one has the wrong photometry). Eight of the nine galaxies with \( F_{UV} N_{uv} ugriz \) detections and 15 of the 21 galaxies with \( N_{uv} ugriz \) detections have fainter \( u \)-light \((\gtrsim 20.5 \text{ mag})\) and larger \( u \)-magnitude errors (see Fig. 9 and the middle panel of Fig. 10). Therefore, these have bluer \( F_{UV}^\text{N} - u^* \) and \( N_{uv} - u^* \) colours and redder \( u' - g' \) colour (such as the \( u' - g' \) colour; see Fig. 8). The larger \( u \)-magnitude error leads to a smaller contribution of the \( u \)-band photometry to the \( \chi^2 \) calculation (see equation 1). The probability function has two peaks for the fit parameters if only optical photometry is used. Even if the UV photometry is included, the high-redshift resolution (at \( z > 2.3 \); see Fig. 7 and the middle panel of Fig. 10) could not have been excluded by the HYPERZ code. This is explained by the fact that the Lyman break would move to a wavelength longer than 3000 Å (i.e. emerge in the \( u \) band) and the 4000-Å break would go beyond the wavelength coverage of the \( ugriz \) filters. Note that the confidence levels are very low in the determinations of both \( \chi^2_{\text{phot}} \) and \( \chi^2_{\text{UV}} \) for most of galaxies in this subsample (cf. Fig. 7).
and low-redshift solutions. From the right panel of Fig. 10 we see that the $P(\chi^2)$ of $z_{\text{spec}}$ is higher than that of $z_{\text{phot}}$.

In summary, the addition of UV photometry would increase the number of non-catastrophic (i.e. $|\Delta z| = |z_{\text{spec}} - z_{\text{phot}}| < 1.0$) identifications, and decrease the mean deviation $\langle \Delta z \rangle$ and standard deviation $\sigma_f (\equiv \sqrt{\Sigma (\Delta z - \langle \Delta z \rangle)^2 / (N - 1)})$ when all galaxies are included. Also, the second spectroscopic subsample of galaxies, for which the photo-$z$ errors are largely decreased by the inclusion of UV data, is mainly located in the redshift $z_{\text{spec}} < 0.2$ and the colour $g^* - r^* \lesssim 0.7$ regions. It has no significant difference in the UV and optical magnitudes in comparison with the first subsample. Therefore, if the galaxy is bluer, we ought to combine the UV and optical photometry to obtain its photo-$z$ estimate. If the $N_{\text{UV}}$ light of a galaxy is too faint, its photo-$z$ estimate would be identified erroneously when UV data are included. If the $u$-light of a galaxy is too faint and the $u$-magnitude error is too large, its photo-$z$ estimate would still be erroneously identified even if UV photometry is included in the HYPERZ code.

4.1.3 Dependence of photo-$z$ accuracy

To investigate the performance of the photo-$z$ estimate in removing catastrophic identifications, in Tables B1–B3 we give the number of non-catastrophic identifications $N$, the mean deviation $\langle \Delta z \rangle$ and the standard deviation $\sigma_f$; as a function of spectroscopic redshift $z_{\text{spec}}$, $g^* - r^*$ colour and $r$ magnitude for models A–D2. Each table includes the cases when using ugriz and $F_{\text{UV}}N_{\text{UV}u\text{griz}}$ photometry. The results in Tables B1–B3 are plotted in Figs 11–13, respectively.

Fig. 11 gives the evolutions of $N$, $\langle \Delta z \rangle$ and $\sigma_f$ with $z_{\text{spec}}$ for models A–D2. First, from the evolution of the mean deviation $\langle \Delta z \rangle$ with $z_{\text{spec}}$, we see that if the ugriz photometry is used the mean photometric redshift $\langle z_{\text{phot}} \rangle = \Sigma z_{\text{phot}} / N$ in the regions of $z_{\text{spec}} \lesssim 0.05$ and $0.25 \lesssim z_{\text{spec}} \lesssim 0.45$ is greater (≈0.05 at the most) and in

(iii) The fourth subsample (nine galaxies) constitutes two galaxies with the full set of photometry and seven galaxies with $N_{\text{UV}u\text{griz}}$ detections. The galaxies in this subsample have fainter $N_{\text{UV}}$ light (see Fig. 9 and the right panel of Fig. 10). Therefore, these have redder $N_{\text{UV}}^*$–optical colours (such as $N_{\text{UV}}^*$–$u^*$ colour; see Fig. 8). Because the fainter $N_{\text{UV}}$ light can also be produced by high-redshift galaxies, for which the Lyman break would move to the $N_{\text{UV}}$ passband, the HYPERZ code is unable to decide between the high-redshift

Figure 9. Distribution of magnitudes (from left to right, $F_{\text{UV}}, N_{\text{UV}}^*, u^*, g^*, r^*, i^*, z^*$) along the wavelength for the four spectroscopic galaxy subsamples, which are divided based on model A. Black dots, red dots, downarrows and uparrows represent the galaxies in the four subsamples, respectively. The horizontal lines represent the corresponding magnitude errors, $\Delta \text{Mag}$. The length of the line located in the upper-left corner denotes $\Delta \text{Mag} = 1$. The galaxies with $F_{\text{UV}}N_{\text{UV}u\text{griz}}$ detections in the third and fourth subsamples are in green and purple, and those with $N_{\text{UV}u\text{griz}}$ detections are in blue and grey. For the sake of clarity, the galaxies in the second, third and fourth subsamples are shifted to the right.

Figure 10. Probability of photometric redshift $P(\chi^2)$ (see equation 1) as a function of redshift for an arbitrary galaxy in the second (left panel), third (middle panel) and fourth (right panel) subsamples based on model A. In each panel, black and red curves (the probability has been reduced by half for the sake of clarity) are when using ugriz and $F_{\text{UV}}N_{\text{UV}u\text{griz}}$ photometry. The red vertical line corresponds to the spectroscopic value. Also, in each panel the magnitudes and their uncertainties, which are multiplied by 5, are plotted for the corresponding galaxy.

Figure 11. Number of non-catastrophic identifications $N$ (squares, ugriz; triangles, $F_{\text{UV}}N_{\text{UV}u\text{griz}}$), mean deviation $(\Delta z)$ (thin lines) and standard deviation $\sigma_f$ (thick lines) (solid line, ugriz; dot-dashed line, $F_{\text{UV}}N_{\text{UV}u\text{griz}}$) as a function of $z_{\text{spec}}$ in removing catastrophic identifications for models A–D2.
Finally, from Fig. 11 we see that the addition of UV photometry significantly increases the number of non-catastrophic identifications in the low-redshift domain for all models.

Fig. 12 presents the evolutions of \(N\), \(\langle \Delta z \rangle\) and \(\sigma_r\) as a function of \(g-r\) colour. It reveals the dependence of photo-z accuracy on \(g-r\) colour. First, from the evolution of \(\langle \Delta z \rangle\) with \(g-r\) colour, we see that when only using \(ugriz\) photometry the mean deviation \(\langle \Delta z \rangle\) is positive in the \(0.8 \lesssim g-r \lesssim 1.4\) region, and is negative in the \(0.3 \lesssim g-r \lesssim 0.8\) region. \(\langle \Delta z \rangle\) increases with decreasing \(g-r\) colour for models A, B, D and D2. For models C and C2, the mean deviation \(\langle \Delta z \rangle\) is less than zero at all \(g-r\) colour bins and \(\langle \Delta z \rangle\) almost does not vary with \(g-r\) colour. The inclusion of UV data can decrease \(\langle \Delta z \rangle\) in the \(0.3 \lesssim g-r \lesssim 0.8\) region for models A, B, D and D2, while increasing \(\langle \Delta z \rangle\) at the redder \(g-r\) colour for models C and C2.

Secondly, from the evolution of \(\sigma_r\) with \(g-r\) colour, we see that the standard deviation in the \(0.8 \lesssim g-r \lesssim 1.2\) region is less than that in the other regions if \(ugriz\) photometry is used. The inclusion of UV data would decrease the standard deviation in the regime \(0.3 \lesssim g-r \lesssim 0.6\) (except for model B) for all models.

Finally, from the correlation between \(N\) and \(g-r\) colour, we see that the addition of UV photometry increases the number of non-catastrophic identifications in the region \(g-r \lesssim 0.8\).

From Fig. 13, which gives the evolutions of \(\langle \Delta z \rangle\), \(\sigma_r\) and \(N\) as a function of \(r\) magnitude, we see that the mean deviation \(\langle \Delta z \rangle\) and standard deviation \(\sigma_r\) are independent of \(r\) magnitude in both cases when using \(ugriz\) and \(F_{uv}\) photometry. The inclusion of UV photometry increases the number of non-catastrophic identifications in the range \(17.0 \lesssim r \lesssim 18.5\), and increases \(\sigma_r\) for all models.

In summary, if catastrophic identifications are removed, the inclusion of UV data increases the number of non-catastrophic identifications in the low-redshift, \(g-r \lesssim 0.8\) and \(17 \lesssim r \lesssim 18.5\) regions and decreases the mean deviation in the high-redshift (\(z_{\text{spec}} \gtrsim 0.5\)) and \(0.3 \lesssim g-r \lesssim 0.8\) region. It also decreases the standard deviation in the \(z_{\text{spec}} \gtrsim 0.3\) and \(0.3 \lesssim g-r \lesssim 0.6\) regions.

### 4.1.4 \(F_{uv}\) or \(N_{uv}\) photometry on photo-z determinations

If we only combine \(F_{uv}\) or \(N_{uv}\) with optical photometry, what would happen? Using the set of \(N_{uv,ugriz}\) photometry, we obtain photo-z estimates \(z_{\text{phot}}\) of galaxies in the spectroscopic sample for models A–D2. We then compare these with the results obtained using the set of \(F_{uv,N_{uv,ugriz}}\) photometry (i.e. \(z_{\text{UV}}\)). Because of size limits, in the top panel of Fig. 14 we only give a comparison between \(z_{\text{phot}}\) and \(z_{\text{UV}}\) for model B. From this, we see that for most of the galaxies \(z_{\text{phot}}\) is lower than 1.0 and \(z_{\text{UV}} < z_{\text{phot}}\). That is to say, only \(N_{uv}\) is combined with \(ugriz\) photometry, the derived photo-z is reasonable for most of the galaxies. The number of non-catastrophic identifications \(N\) is increased, but the mean deviation and standard deviations are increased in comparison with those when using \(F_{uv,N_{uv,ugriz}}\) photometry (because \(z_{\text{phot}} > z_{\text{UV}}\)). The reason that the inclusion of \(N_{uv}\) light decreases the probability of the solution in the region of \(1.8 \lesssim z \lesssim 2.4\) is that the Lyman break would emerge in the \(N_{uv}\) passband. The overestimation of photo-z is explained by the fact that the main spectral feature is still the 4000-Å break, which is unable to break the degeneracy among the fit parameters if \(z \lesssim 0.6\).

Using the set of \(F_{uv,ugriz}\) photometry, we also obtain photo-z estimates \(z_{\text{phot}}\) for the spectroscopic galaxy sample. In the bottom panel of Fig. 14, we give a comparison between \(z_{\text{UV}}\) and \(z_{\text{phot}}\).
Effects of UV photometry on photo-z

Figure 14. Comparison between \( z_{NUV}^{phot} \) and \( z_{UV}^{phot} \) (top panel, based on model B) and comparison between \( z_{FUV}^{phot} \) and \( z_{UV}^{phot} \) (bottom panel, based on model B) for the spectroscopic galaxy sample. The lines, symbols and colours have the same meaning as in Fig. 7, but the y-axis represents \( z_{NUV}^{phot} \) or \( z_{FUV}^{phot} \), respectively.

for model B. From this, we see that \( z_{FUV}^{phot} \) is close to \( z_{spec} \). The agreement is caused by the fact that the Lyman break would emerge in the \( F_{UV} \) passband if the redshift were low. The above conclusions are also true for the other models.

In Tables B1–B3 we also give \( N, \langle \Delta z \rangle \) and \( \sigma \), of model B as a function of redshift, \( g-r \) and \( r \) magnitude when using \( N_{UVugriz} \) or \( F_{UVugriz} \) photometry. From these, we see that the catastrophic objects mainly are those galaxies with \( z_{spec} \lesssim 0.3, g-r \gtrsim 0.8 \) and \( r \gtrsim 18 \) mag when \( N_{UV} \) photometry is combined with optical photometry. Also, we see that the catastrophic objects are those galaxies with \( z_{spec} \lesssim 0.15, 0.4 \lesssim g-r \lesssim 1.0 \) and \( 16.5 \lesssim r \lesssim 18 \) mag if \( F_{UV} \) photometry is combined with optical data. That is to say, only including \( N_{UV} \) or \( F_{UV} \) photometry would cause erroneous photo-z estimates for those faint ‘redder’ high-redshift galaxies and those ‘bluer’ low-redshift (intermediate \( r \) magnitude) galaxies, respectively. The number of catastrophic identifications when using \( F_{UVugriz} \) photometry is less than when using \( N_{UVugriz} \) photometry.

4.2 Binary interactions on photo-z determinations

Binary interactions would significantly change the UV spectra of populations at age \( t \gtrsim 1 \) Gyr (see Fig. 1). Using the HPL07-b, HPL07-s, Yunnan-b and Yunnan-s population synthesis models, we obtain the \( F_{UV}, N_{UV}, u, g, r, i \) and \( z \) magnitudes of a solar-metallicity population with a mass of \( 1 \) M\(_\odot\). In comparison, we find that the differences in the \( N_{UV}, u, g, r, i \) and \( z \) magnitudes among these models are slight, while the difference in the \( F_{UV} \) magnitude caused by binary interactions (i.e. that between the HPL07-s and HPL07-b models or that between the Yunnan-s and Yunnan-b models) is significant at \( \log(t \text{ yr}^{-1}) \gtrsim 9.0 \) (see Fig. 15). Then, we ask whether binary interactions would affect photo-z estimates.

Comparing the photo-z estimates of galaxies in the spectroscopic sample between models C and C2 (Fig. 5), and those between models D and D2 (Fig. 6), we find that binary interactions do not systematically affect photo-z determinations. One reason for this is that binary interactions vary significantly the SEDs of populations (or burst-type galaxies) only at late ages (\( t \gtrsim 1 \) Gyr). Thus, at redshift \( z = 0 \) the difference in the SEDs, \( F_{UV}, N_{UV}, u, g, r, i \) and \( z \) magnitudes of non-burst galaxies between models C and C2 and between models D and D2 is slight for a given age and galaxy type.

In Fig. 16 we give the \( F_{UV} \) magnitude of burst, E, S0 and Sa–Sd galaxies at redshift \( z = 0 \) using the Yunnan-s and Yunnan-b models. Even at redshift \( z = 0.6 \), the binary interactions only make the SEDs of populations (or burst-type galaxies) bluer in the regime \( \lambda < 4000 \) Å, according to \( z \approx (\lambda' - \lambda_0) / \lambda_0 \) and \( \lambda_0 = 2500 \) Å, beyond which the effect of binary interactions on the SEDs is slight. These bluer
Figure 16. $F_{\text{UV}}$ magnitude of a solar-metallicity galaxy (1 $M_{\odot}$) at $z = 0$. Solid circles, squares, up-triangles, left-triangles, right-triangles, down-triangles and star symbols are for burst, E, S0, Sa, Sb, Sc and Sd galaxies, respectively. The grey and coloured symbols (black, red, green, blue, cyan, magenta and yellow correspond to burst, E, S0–Sd types, respectively) denote the use of the Yunnan-s and Yunnan-b models, respectively.

Figure 17. Evolutions of $N$ (top panels), $|\langle \Delta z \rangle|$ (middle panels) and $\sigma_z$ (bottom panels) as a function of $z_{\text{spec}}$ for models A–D2 in removing catastrophic identifications. Left and right panels are when using $ugriz$ and $F_{\text{UV}}N_{\text{UV}ugriz}$ photometry, respectively.

UV and near-optical SEDs can be easily offset by the decrements of visual extinction $A_V$ and age, the absence of the Lyman break and the adoption of the different reddening laws during the fitting process.

In Figs 17–19 (generated from Tables B1–B3, respectively), we present $N$, the absolute value of mean deviation $|\langle \Delta z \rangle|$ and $\sigma_z$ as a function of $z_{\text{spec}}$, $g-r$ colour and $r$ magnitude for models A–D2 in both cases when using $ugriz$ and $F_{\text{UV}}N_{\text{UV}ugriz}$ photometry; also, the catastrophic identifications are removed. From Figs 17–19, we see that binary interactions decrease and increase $|\langle \Delta z \rangle|$ in the regions of $0.3 \lesssim g-r \lesssim 0.8$ and $r \gtrsim 17.8$ mag, respectively, when using optical photometry (see the comparisons between models D and D2 in Figs 18 and 19). These decrease the standard deviation $\sigma_z$ at all $r$ magnitudes for both cases when using $ugriz$ and $F_{\text{UV}}N_{\text{UV}ugriz}$ data (see Fig. 19).

In Fig. 20, we present the per cent difference in the number of non-catastrophic identifications between models C and C2 and between models D and D2 ($dN \equiv (N_{x2} - N_{x1})/N_{x1}$, $x = C$ or D) as a function of $z_{\text{spec}}$, $g-r$ colour and $r$ magnitude. From this, we see that $N_{\text{D2}}$ is less than $N_{\text{D}}$ at $0.2 \lesssim z_{\text{spec}} \lesssim 0.3$ in both cases.
for $\sigma$, when using $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ data) are significantly different. Also, $|\langle \Delta z \rangle|$ and $\sigma$, of model B are significantly lower than those of the other models for both cases when using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry.

Finally, from the middle and bottom panels of Fig. 19, we see that the mean and standard deviations of models C and C2 are greater than those of the other models in both cases when using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry. In the intermediate $r$-magnitude region, $|\langle \Delta z \rangle|$ of models A, D and D2 are lower in both cases when using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry.

From the above comparisons, we see that when using $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry the number of non-catastrophic identifications is similar for all models. When using $ugriz$ photometry, the number of non-catastrophic identifications of model B is greater than for the other models in the low-redshift, bluer $g-r$ and faint $r$-magnitude regions. When using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry, the mean and standard deviations of model B are lower at $g-r \lesssim 0.7$, and $|\langle \Delta z \rangle|$ of models A, D and D2 are relatively lower at almost all redshift bins and at intermediate $r$ magnitudes.

## 5 Ultraviolet photometry and binary interactions on galaxy morphology

Bolzonella et al. (2000) have claimed that the HYPERZ code allows us to obtain photo-$z$ estimates and best-fitting parameters across the whole space of galaxy. Because of the lack of spectral resolution, only rough spectral types can be retrieved from broad-band photometry. In other words, early types can be reliably and easily identified, while late types are usually misidentified because of the degeneracy between spectral type, age of the stellar population and visual extinction.

Using the HYPERZ code and the morphological sample of 1502 galaxies, which are from the catalogue of Fukugita et al. (2007) and have matched with SDSS DR7 and GALEX DR4 (see Section 3 for details), we recover their morphological types by using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry for models A–D2, respectively. The corresponding galaxy types of the morphological index of Fukugita et al. (2007), $T$(Fuk), and ours, $T$(Ours), are presented in Table 3. Note that half-integer classes are allowed for $T$(Fuk).

In Figs 21 and 22, we give the histograms of $r$ magnitude and spectroscopic redshift $z_{\text{spec}}$ distributions, respectively, for E, S0, Sa–Sd and Irr subsamples. Fig. 23 gives the histogram of the $T$(Fuk) distribution for the morphological sample. From these, we see that the galaxies in the morphological sample are relatively bright

![Figure 20](https://example.com/figure20.png)

**Figure 20.** The per cent difference in the number of non-catastrophic identifications $dN$ ([($N_{\text{C2}} - N_{\text{C}})/N_{\text{C2}}$, $x = \text{C or D}$] between models C and C2 (squares) and between models D and D2 (triangles) as a function of $z_{\text{spec}}$ (left panels), $g-r$ colour (middle panels) and $r$ magnitude (right panels). Top and bottom panels are when using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry, respectively.

### 4.3 EPS models on photo-$z$ determinations

First, from the evolutions of the number of non-catastrophic identifications $N$ with $z_{\text{spec}}$, $g-r$ colour and $r$ magnitude in the top panels of Figs 17–19, we see that the difference in $N$ among models A–D2 is smaller if $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ data are used. We see that $N$ decreases from model B, model A, models D/D2 to C/C2 (i.e. $N_B > N_A > N_D/D2 > N_C/C2$) in the regions $0.05 \lesssim z_{\text{spec}} \lesssim 0.15$, $0.3 \lesssim g-r \lesssim 0.8$ and $17 \lesssim r \lesssim 18.2$ mag when only optical data are used.

Secondly, from the middle and bottom panels of Fig. 17, we see the following. (i) The absolute values of the mean deviation $|\langle \Delta z \rangle|$ and standard deviation $\sigma$, of models C/C2 are greater than those of the other models in the low-redshift domain for both cases when using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry. (ii) Among models A, B, D and D2, the difference of $|\langle \Delta z \rangle|$ in the regions $z_{\text{spec}} \lesssim 0.05$ and $z_{\text{spec}} \gtrsim 0.5$ and the difference of $\sigma$, in the region $z_{\text{spec}} \gtrsim 0.5$ are larger (except for $\sigma$, when using $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ data). Furthermore, in the $0.1 \lesssim z_{\text{spec}} \lesssim 0.5$ region, $|\langle \Delta z \rangle|$ and $\sigma$, of model B are greater than those of models A, D and D2 for both cases when using $ugriz$ and $F_{\mathrm{UV}}N_{\mathrm{UV}}ugriz$ photometry (except for $\sigma$, when using optical data in the $0.3 \lesssim z_{\text{spec}} \lesssim 0.4$ region). (iii) The evolutions of $|\langle \Delta z \rangle|$ and $\sigma$, with redshift of models D and D2 are similar to those of model A.

Moreover, from the middle and bottom panels of Fig. 18, we see that in the $g-r \lesssim 0.7$ region, $|\langle \Delta z \rangle|$ and $\sigma$, of these models (except

### Table 3. 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        |
Therefore, we compare $r$ and $N$ (Fuk) here. Here, $\sigma$ (Fuk) increases with $\sigma$ of all models for 2. For models A–D2, $\sigma$ decreases significantly. The following comparisons of $|\langle \Delta T \rangle|$ and $\sigma_T$ are based on bins with $N_i \geq 10$ because a small value of $N_i$ would lead to a larger error in $|\langle \Delta T \rangle|$ and $\sigma_T$. In each panel of Figs C1–C3, the two vertical lines indicate where $N_i = 10$. Therefore, we compare $|\langle \Delta T \rangle|$ and $\sigma_T$ in the region enclosed by the two horizontal lines (the shaded region of Figs C1–C3). First, from Fig. C1, we see that the inclusion of UV light increases $N_i$ of all models for $T(Fuk) \geq 1.0$ [the increment increases with $T(Fuk)$], decreases $|\langle \Delta T \rangle|$ and $\sigma_T$ of models C and C2 for $T(Fuk) = 0.0–0.5$ at all redshift bins and for $1.0 \leq T(Fuk) \leq 3.0$ (except when $z_{\text{spec}} = 2.5$) at $z_{\text{spec}} \lesssim 0.04$, and also decreases $|\langle \Delta T \rangle|$ and $\sigma_T$ of models A and B for $T(Fuk) = 2.0–2.5$ at all redshift bins. Moreover, we also see that all models have similar trends of $|\langle \Delta T \rangle|$ and $\sigma_T$ with redshift for a given $T(Fuk)$ when the full set of photometry is used. Both $|\langle \Delta T \rangle|$ and $\sigma_T$ are independent of $z_{\text{spec}}$ for all galaxy types, and $|\langle \Delta T \rangle|$ increases with $T(Fuk)$ [except for models C and C2, for which $|\langle \Delta T \rangle|$ is independent of $T(Fuk)$]. Secondly, from Fig. C2, we see that the inclusion of UV data increases $N_i$ of all models for $2.5 \leq T(Fuk) \leq 4.0$ in the blue $g-r$ region (correspondingly, the left vertical line moves blueswards

![Figure 21. Histogram of $r$-magnitude distribution for E (thick black solid line), S0 (thick red dashed line), Sa (thick green dot-dashed line), Sb (thick blue dotted line), Sc (thick magenta dashed-dot-dot-dot line), Sd (thin grey solid line) and Irr (thin grey dashed line) morphological subsamples (see text in Section 3). Note that the half-integer classes are designated as the corresponding integer classes in this figure.](image)

![Figure 22. Similar to Fig. 21, but for spectroscopic redshift $z_{\text{spec}}$. The left panel is for E, S0 and Sa types and the right panel for Sb, Sc, Sd and Irr types. The lines have the same meanings as in Fig. 21. (r < 16. mag; see Fig. 21) and their redshifts are less than 0.2 (see Fig. 22). Most of these belong to early types; Sd and Irr types are scarce (see Fig. 23).](image)

![Figure 23. Histogram of the morphology index $T(Fuk)$ distribution for the morphological galaxy sample. The grey solid line is for the original catalogue of Fukugita et al. (2007) and the red dotted line is for the sample of galaxies matched with SDSS DR7 and GALEX DR4. Also shown is the sample of galaxies only matched with the SDSS DR7 (black solid line). The corresponding galaxy types of $T(Fuk)$ are given in Table 3.](image)
Effects of UV photometry on photo-z

Figure 24. Comparisons in the morphological index of galaxies between ours and those of Fukugita et al. (2007) for models A–D2. Black and red squares represent using $ugriz$ and $F_{UV}$ photometry, respectively, and their area represents the number of galaxies on the grid. In the upper-left corner of each panel we show that the number of galaxies is 50. Crosses show the correlation between $T$(Ours) and $T$(Fuk).

5.2 Binary interactions on morphological types

To obtain the influence of binary interactions on the retrieved morphological index, in Fig. 26 we give the difference in the number of non-catastrophic objects between models D and D2 on the plane of $T$(Ours) and $T$(Fuk) for $ugriz$ and $F_{UV}N_{ugriz}$ photometry.

From Figs 24 and 26, we see that the inclusion of binary interactions mainly affects the determinations of E and S0 types in both cases when using optical and the full set of photometry. The difference when using optical photometry is more significant than when using $F_{UV}N_{ugriz}$ photometry. This is explained by the fact that binary interactions make the UV flux of burst-type galaxies higher only at log($t$ yr$^{-1}$) $\gtrsim$ 9, and these bluer UV spectra can be offset by the variation of other parameters (such as the decrements of age and visual extinction, etc.) during the fitting process (see also the discussion in Section 4.2).
5.3 Comparison with other morphology selection criteria

In this section, we give a comparison of the performance of selecting early-type (E, S0 and Sa) and late-type (Sb, Sc, Sd and Irr) galaxies when using the HYPERZ code (this work) and when using the three morphology-sensitive parameters (the concentration index C, the profile likelihood and u–r colour). The concentration index C is defined as the ratio of the radii containing 90 and 50 per cent of the Petrosian r galaxy light (i.e. \( C \equiv r_{90}/r_{50} \)). The profile likelihood is defined as the difference between the de Vaucouleurs (\( P_{\text{de V}} \)) and exponential (\( P_{\text{exp}} \)) profile likelihoods in the r band.

Tables 4 and 5 give the reliability and completeness for selecting early- and late-type galaxies using the HYPERZ code (including models A–D2) and using the three morphology selection criteria (\( C = 2.6, P_{\text{exp}} - P_{\text{de V}} = 0 \) and \( u-r = 2.22 \)). The definitions of reliability and completeness are from Strateva et al. (2001): the reliability of the classification is the fraction of galaxies from the selected subsample that are correctly classified; the completeness is the fraction of all galaxies of a given type from the original sample that are selected by the classification scheme.

From Tables 4 and 5, we see that the reliability for early-type selection using the HYPERZ code (including all models) is similar to that using the three morphology selection criteria, while the completeness is lower in comparison. Also, the reliability and completeness for selecting late-type galaxies (except for models C and C2) using the HYPERZ code is less than those when using the three morphology criteria.

5.4 New morphology selection criteria

Plotting the galaxies in the morphological sample in colour–colour diagrams (Fig. 27), we find that \( F_{\text{UV}}-u \) and \( N_{\text{UV}}-u \) can be used as new morphology indicators. Table 6 presents the reliability and completeness for selecting early- and late-type galaxies using the \( F_{\text{UV}}-u = 3.16 \) and \( N_{\text{UV}}-u = 1.94 \) separators. We find that the reliability and completeness for both early- and late-type selection for \( N_{\text{UV}}-u = 1.94 \) colour separator are comparable to the concentration index criterion (\( C = 2.6 \)). The \( N_{\text{UV}}-u = 1.94 \) colour separator has higher completeness (73 per cent) for late-type selection than the \( u-r = 2.22 \) colour separator (40 per cent). Moreover, the \( F_{\text{UV}}-u = 3.16 \) colour separator has lower completeness for selecting early-type galaxies and lower reliability for selecting late-type galaxies than the \( C = 2.6 \), profile likelihood \( P_{\text{de V}} = P_{\exp} \) and \( u-r = 2.22 \) separators. This is explained by the fact that Sa-type galaxies show more scatter in \( F_{\text{UV}}-u \) colour.

If the galaxies have not been detected in the \( N_{\text{UV}} \) passband, we can construct the morphology selection criterion by combining their optical photometry with \( F_{\text{UV}} \) photometry. As such, we construct a morphology selection separator of 5.77–1.47\((u-r)-(F_{\text{UV}}-u)\) = 0. In comparison, we find that the reliability and completeness of this separator for both early- and late-type selection are comparable to \( C = 2.6 \) and \( N_{\text{UV}}-u = 1.94 \) selection criteria (see Table 6); it has higher completeness for selecting late-type galaxies than the \( u-r = 2.22 \) separator. Similarly, we also construct the 5.27–1.30\((u-r)-(N_{\text{UV}}-u)\) = 0 separator. We find that this criterion has similar reliability and completeness for both early- and late-type selection as the \( N_{\text{UV}}-u = 1.94 \) criterion (i.e. the performance of early- and late-type selection has not been improved even if the optical photometry is combined with \( N_{\text{UV}}-u \) colour). Fig. 27 presents the lines corresponding to the morphology selection separators, in the diagrams of \( (F_{\text{UV}}-u) \) versus \((u-r)\) and \( (N_{\text{UV}}-u) \) versus \((u-r)\).

**Table 4.** Reliability and completeness for early- and late-type selection by the HYPERZ code (including models A–D2). The upper and lower parts correspond to using \( ugriz \) and \( F_{\text{UV}} N_{\text{UV}} ugriz \) photometry, respectively. This table is based on the morphology sample of 1502 galaxies.

| Model | Early type | Late type | \( ugriz \) | \( F_{\text{UV}} N_{\text{UV}} ugriz \) |
|-------|------------|-----------|-------------|------------------|
|       | Reliability | Completeness | Reliability | Completeness |
| A     | 0.74       | 0.60       | 0.62        | 0.54            |
| B     | 0.69       | 0.60       | 0.58        | 0.46            |
| C     | 0.83       | 0.39       | 0.54        | 0.73            |
| C2    | 0.85       | 0.40       | 0.54        | 0.74            |
| D     | 0.72       | 0.58       | 0.60        | 0.53            |
| D2    | 0.74       | 0.63       | 0.65        | 0.52            |

**Table 5.** Reliability and completeness for selecting early- and late-type galaxies using the three morphology selection parameters: the concentration index C, profile likelihood and u–r colour.

| Selection rule | Reliability | Completeness |
|----------------|-------------|--------------|
| Early type     |             |              |
| \( C > 2.6 \)  | 0.83        | 0.74         |
| \( P_{\text{de V}} > P_{\text{exp}} \) | 0.76 | 0.77 |
| \( u-r \geq 2.22 \) | 0.71 | 0.75 |
| Late type      |             |              |
| \( C < 2.6 \)  | 0.82        | 0.62         |
| \( P_{\text{de V}} < P_{\text{exp}} \) | 0.85 | 0.49 |
| \( u-r \leq 2.22 \) | 0.77 | 0.40 |
6 SUMMARY AND CONCLUSIONS

Using the HYPERZ code of Bolzonella et al. (2000) and a template spectral library consisting of four observed galaxy spectra from CWW and eight spectral families built with the GISSEL98, BC03, HPL07 and Yunnan EPS models, we present photometric redshift estimates for a spectroscopic sample of galaxies that are selected randomly from the SDSS DR7 and GALEX DR4. We present morphological types for a morphological sample of bright galaxies, which are also matched with the SDSS DR7 and GALEX DR4.

Based on the spectroscopic galaxy sample, we find that the inclusion of $F_{UV}$ or $N_{UV}$, or both, can decrease the number of catastrophic identifications ($|z_{spec} - z_{phot}| > 1.0$). When using $F_{UVugriz}$ and $N_{UVugriz}$ photometry, the number of non-catastrophic identifications is lower than when using $F_{UV}N_{UVugriz}$ (i.e., $N_{FUV}N_{UVugriz} > N_{FUVugriz} > N_{UVugriz}$). When using $F_{UV}N_{UVugriz}$ photometry, the catastrophic objects are the galaxies with blue $g-r$ colour and low spectroscopic redshift. When using $N_{UVugriz}$ photometry, they are the faint 'redder' high-redshift galaxies. When using $F_{UVugriz}$ photometry, the catastrophic identifications are the 'bluer' low-redshift galaxies. If GALEX $F_{UV}$ photometry or both $F_{UV}$ and $N_{UV}$ photometry are combined with $ugriz$ data, the difference between the photometric and spectroscopic redshifts is within 0.2 for the majority of non-catastrophic objects. If only $N_{UV}$ is combined, the derived photo-zs are systematically greater than their spectroscopic counterparts.

If catastrophic identifications are removed, the inclusion of both $F_{UV}$ and $N_{UV}$ photometry can increase the number of non-catastrophic identifications in the low-redshift, $g-r \lesssim 0.8$ and faint $r$-magnitude regions, decrease the mean deviation $|\Delta z|$ in the $z_{spec} \gtrsim 0.5$ and $0.3 \lesssim g-r \lesssim 0.8$ regions (except for models C and C2) and decrease the standard deviation $\sigma$ in the $z_{spec} \gtrsim 0.3$ and $0.3 \lesssim g-r \lesssim 0.6$ regions. Moreover, if a galaxy has fainter $u$ light, its photo-z estimate would still be erroneously identified even if UV photometry is included. If a galaxy has fainter $N_{UV}$ light, its photo-z estimate would be erroneously identified when UV photometry is included. Binary interactions mainly can increase the number of non-catastrophic identifications and decrease the mean and standard deviations in the $0.3 \lesssim g-r \lesssim 0.8$ region when only using optical photometry.

Based on the morphological galaxy sample, we confirm that early-type galaxies can be easily retrieved and late-type galaxies are often misidentified as early types. We find that the inclusion of UV photometry decreases and increases the probability that early types are classified as burst and E types, respectively, and increases the probability that late types are classified as CWW-Sbc and CWW-Scd types. If catastrophic identifications are excluded, the inclusion of UV data increases the number of retrieved late-type galaxies in all redshift, blue $g-r$ and $r \gtrsim 14$ regions; the increment increases with $7(F_{UV})$. Binary interactions mainly affect the determination of E and S0 types.

In comparison, we find that the reliability and completeness for early- and late-type selection using the HYPERZ code are much lower than those when using the three morphology criteria: the concentration index $C = 2.6$, the profile likelihood $P_{exp} = P_{exp}$ and $u-r = 2.22$. Moreover, we find that $N_{UV} \lesssim 1.94$ can be used as a new morphology selection indicator. Its reliability and completeness for selecting early and late types are approximately the same as those of the $C = 2.6$ criterion; even its completeness for selecting early types is greater than that of the $u-r = 2.22$ criterion. The criterion of $F_{UV} \lesssim 3.16$ is not as
good as \( N_{uv-w} = 1.94 \), while the criterion constructed by the combination of \( F_{uv-w} \) with \( u-r \) colour, 5.77 \( - 1.47(u-r) = F_{uv-w} \), can reach similar reliability and completeness for early- and late-type selection to those of \( N_{uv-w} = 1.94 \). For the new constructed criteria \( 5.27 - 1.30(u-r) = N_{uv-w} \), the reliability and completeness for early- and late-type selection are not improved in comparison with the \( N_{uv-w} = 1.94 \) criterion.

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APPENDIX A: INFLUENCE OF INPUT PARAMETERS ON PHOTO-z DETERMINATIONS

In this appendix, our standard is model B. To investigate the effect of the input parameters on photo-z estimates, we proceed by changing each parameter in turn, while the other parameters remain the same as in the standard model. Model Ba uses the reddening law of Seaton (1979) instead of Calzetti et al. (2000). Model Bb uses the set of cosmological parameters \((1.0, 0.0, 70)\) instead of \((0.3, 0.7, 70)\). Models Be and Bd use the minimum magnitudes \((29.5, 29.5, 30, 30, 30, 30, 30)\) instead of \((29.5, 29.5, 30, 30, 30, 30, 30)\). Models Bg and Bf use the eight theoretical spectral families and CWW spectra, respectively. Model Bg uses the set of cosmological parameters \((1.0, 0.0, 50)\) instead of \((0.3, 0.7, 70)\).

We obtain photo-z estimates of galaxies in the spectroscopic sample for models Ba–Bf using \( ugriz \) and \( F_{uv-N_{uv} ugriz} \) photometry. Figs A1–A3 present the differences in the number of
**Figure A1.** Differences in $N$ (top panels), $|\langle \Delta z \rangle|$ (middle panels) and $\sigma_z$ (bottom panels) between model B and the other models Ba–Bg as a function of $z_{\text{spec}}$ in removing catastrophic identifications. Left and right panels are when using ugriz and $F_{\text{UV}}N_{\text{uvgriz}}$ photometry, respectively.

**Figure A2.** Similar to Fig. A1, but as a function of $g-r$ colour.

**Figure A3.** Similar to Fig. A1, but as a function of $r$ magnitude.

non-catastrophic identifications ($\Delta N$), mean ($\langle |\Delta z| \rangle$) and standard deviation ($\Delta \sigma_z$) deviations between model B and the other models Ba–Bg as a function of redshift, $g-r$ colour and $r$ magnitude in removing catastrophic identifications, respectively. From these, we see the following.

(i) If the reddening law of Seaton (1979) (model Ba) is used, the number of non-catastrophic identifications $N$ increases when using optical photometry, and the mean and standard deviations (except when using $F_{\text{UV}}N_{\text{uvgriz}}$ photometry) differ significantly from those of model B.

(ii) If the minimum magnitude error is set to 0.001 (model Bc, one-fiftieth of the value in model B), the number of non-catastrophic identifications $N$ and the mean and standard deviations in the bluer $g-r$ region are greater than those of model B when only using optical photometry.

(iii) If only the theoretical spectral template (model Be) or only the CWW set of empirical spectra (model Bf) is used, the number of non-catastrophic identifications would be increased or decreased when using optical photometry, respectively. The standard deviation is not changed significantly, and the mean deviation of model Bf is greater than that of model Be.

(iv) Decreasing the set of minimum magnitude (model Bb) or increasing the minimum magnitude error by a factor of 2 (0.1, model Bd) or using the set of cosmological parameters (1.0, 0.0, 70) would not significantly vary the results.

**APPENDIX B: DEPENDENCE OF PHOTO-z ACCURACY ON REDSHIFT, COLOUR, MAGNITUDE AND THE FILTER SET**

Tables B1–B3 give the number of non-catastrophic identifications $N$, standard deviation $\sigma_z$ and mean deviation $\langle \Delta z \rangle$ as a function of spectroscopic redshift $z_{\text{spec}}$, $g-r$ colour and $r$ magnitude in removing catastrophic identifications for models A–D2. Each table includes the cases of using ugriz, $F_{\text{UV}}N_{\text{uvgriz}}$, $F_{\text{UV}}ugriz$ (only for model B) and $N_{\text{uvgriz}}$ (only for model B) photometry.
Table B1. Number of non-catastrophic identifications $N$, standard deviation ($\sigma_z$) and mean deviation ($\langle \Delta z \rangle$) of galaxies in the spectroscopic sample as a function of the redshift bin and the filter set for models A–D2. The first line gives the number of galaxies in the corresponding redshift bin. The following first and second parts of the table give the results when $ugriz$ and $B$ photometry is used for all models. The third and fourth parts give the results when $N_{UV}$ and $F_{UV}$ photometry is used for model B. All results are for removing catastrophic identifications.

| $z$ = 0.0–0.05 | $z$ = 0.05–0.10 | $z$ = 0.10–0.15 | $z$ = 0.15–0.20 | $z$ = 0.20–0.30 | $z$ = 0.30–0.40 | $z$ = 0.40–0.50 | $z$ = 0.50–0.60 |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ |
| All | 1114 | 2395 | 1796 | 783 | 288 | 101 | 47 | 5 |
| A | 722, 0.054, −0.35 | 1658, 0.041, 0.003 | 1573, 0.045, 0.017 | 765, 0.045, 0.011 | 279, 0.056, 0.004 | 87, 0.085, −0.047 | 41, 0.082, 0.017 | 5, 0.064, −0.032 |
| B | 741, 0.054, −0.22 | 1881, 0.040, 0.012 | 1680, 0.045, 0.025 | 771, 0.046, 0.014 | 279, 0.064, −0.007 | 87, 0.077, −0.061 | 41, 0.086, −0.001 | 5, 0.068, −0.022 |
| C | 673, 0.061, −0.06 | 1471, 0.058, −0.022 | 1407, 0.060, −0.022 | 724, 0.055, −0.027 | 273, 0.062, −0.036 | 86, 0.069, −0.058 | 40, 0.086, −0.016 | 5, 0.067, −0.019 |
| D | 666, 0.061, −0.06 | 1464, 0.059, −0.021 | 1405, 0.061, −0.020 | 723, 0.056, −0.025 | 271, 0.061, −0.038 | 80, 0.069, −0.065 | 40, 0.086, −0.016 | 4, 0.058, −0.047 |
| E | 693, 0.058, −0.042 | 1567, 0.044, 0.001 | 1538, 0.049, 0.012 | 756, 0.048, 0.008 | 278, 0.058, 0.002 | 87, 0.085, −0.050 | 41, 0.092, 0.015 | 5, 0.104, 0.003 |
| F | 706, 0.055, −0.039 | 1609, 0.042, 0.003 | 1550, 0.046, 0.015 | 738, 0.046, 0.011 | 250, 0.058, −0.005 | 81, 0.082, −0.052 | 35, 0.086, 0.016 | 4, 0.051, −0.050 |
| $N_{UV}$, non-cata. | | | | | | | | |
| A | 1109, 0.056, −0.027 | 2385, 0.049, 0.009 | 1790, 0.052, 0.021 | 780, 0.049, 0.016 | 283, 0.059, −0.001 | 94, 0.073, −0.040 | 44, 0.050, 0.015 | 5, 0.080, 0.019 |
| B | 1100, 0.055, −0.023 | 2384, 0.049, 0.016 | 1790, 0.055, 0.027 | 781, 0.056, 0.014 | 283, 0.064, −0.008 | 93, 0.081, −0.050 | 44, 0.049, 0.018 | 5, 0.081, 0.021 |
| C | 1111, 0.066, −0.043 | 2382, 0.064, −0.021 | 1791, 0.066, −0.027 | 780, 0.064, −0.035 | 283, 0.069, −0.051 | 92, 0.071, −0.070 | 42, 0.066, −0.040 | 5, 0.067, −0.053 |
| D | 1109, 0.061, −0.038 | 2383, 0.053, 0.001 | 1790, 0.053, 0.013 | 780, 0.051, 0.014 | 283, 0.058, −0.003 | 93, 0.079, −0.044 | 44, 0.048, 0.020 | 5, 0.103, 0.038 |
| E | 1109, 0.061, −0.036 | 2381, 0.052, 0.003 | 1788, 0.052, 0.015 | 777, 0.051, 0.012 | 279, 0.061, −0.007 | 91, 0.078, −0.052 | 41, 0.050, 0.018 | 4, 0.084, 0.000 |
| $N_{UV}$, non-cata. | | | | | | | | |
| B | 1091, 0.107, −0.367 | 2337, 0.101, −0.361 | 1779, 0.100, −0.400 | 765, 0.097, −0.434 | 236, 0.088, −0.450 | 42, 0.082, −0.440 | 14, 0.123, −0.457 | 1, 0.337 |
| $F_{UV}$, non-cata. | | | | | | | | |
| B | 1090, 0.063, −0.033 | 2334, 0.046, 0.013 | 1781, 0.051, 0.020 | 776, 0.049, 0.010 | 280, 0.058, −0.011 | 88, 0.083, −0.051 | 42, 0.076, 0.002 | 5, 0.066, −0.022 |
Table B2. Similar to Table B1, but for the bin of $g-r$ colour.

| $g-r$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ | $N, \sigma_z, \langle \Delta z \rangle$ |
|-------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
|       | All                                  | A                                   | B                                   | C                                   | D                                   | C2                                  | D2                                  |
| 0.0–0.2 | 17                                   | 344                                 | 1109                                | 1628                                 | 2050                                | 897                                 | 230                                 | 91(160)                              |
| 0.2–0.4 |                                     | 64, 0.059, −0.041 486, 0.067, −0.028 | 1212, 0.044, −0.011 2018, 0.040, 0.015 | 896, 0.046, 0.018 228, 0.044, 0.008 | 86, 0.081, −0.023 |
| 0.4–0.6 |                                     |                                      |                                      |                                      |                                      |                                      |                                      |                                      |
| 0.6–0.8 |                                     |                                      |                                      |                                      |                                      |                                      |                                      |                                      |
| 0.8–1.0 |                                     |                                      |                                      |                                      |                                      |                                      |                                      |                                      |
| 1.0–1.2 |                                     |                                      |                                      |                                      |                                      |                                      |                                      |                                      |
| 1.2–1.4 |                                     |                                      |                                      |                                      |                                      |                                      |                                      |                                      |
| 1.4–1.6 |                                     |                                      |                                      |                                      |                                      |                                      |                                      |                                      |
Table B3. Similar to Table B1, but for the $r$-magnitude bin.

|       | $N, \sigma_z \langle \Delta z \rangle$ | $N, \sigma_z \langle \Delta z \rangle$ | $N, \sigma_z \langle \Delta z \rangle$ | $N, \sigma_z \langle \Delta z \rangle$ | $N, \sigma_z \langle \Delta z \rangle$ | $N, \sigma_z \langle \Delta z \rangle$ |
|-------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| All   | (130) 149                              | 275                                    | 478                                    | 929                                    | 1498                                    | 1192                                   |
| A     | 117, 0.041, −0.005                      | 212, 0.051, −0.008                     | 358, 0.043, 0.003                      | 660, 0.047, −0.002                     | 1062, 0.050, 0.002                      | 1353, 0.050, 0.008                      |
| B     | 124, 0.041, 0.001                       | 225, 0.045, 0.005                      | 383, 0.036, 0.014                      | 726, 0.046, 0.009                      | 1171, 0.049, 0.012                      | 1674, 0.046, 0.016                      |
| C     | 122, 0.061, −0.039                      | 202, 0.061, −0.027                     | 328, 0.057, −0.019                     | 583, 0.060, −0.028                     | 945, 0.062, −0.029                      | 1345, 0.060, −0.027                     |
| C2    | 120, 0.059, −0.039                      | 201, 0.062, −0.029                     | 326, 0.058, −0.018                     | 579, 0.061, −0.025                     | 944, 0.062, −0.028                      | 1340, 0.061, −0.026                     |
| D     | 115, 0.048, −0.010                      | 208, 0.054, −0.008                     | 351, 0.048, −0.001                     | 627, 0.051, −0.003                     | 1013, 0.054, −0.002                     | 1478, 0.053, 0.003                      |
| D2    | 118, 0.047, −0.010                      | 213, 0.051, −0.013                     | 355, 0.043, 0.001                      | 638, 0.049, −0.001                     | 1035, 0.051, 0.002                     | 1491, 0.049, 0.007                      |

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**APPENDIX C: DEPENDENCE OF MORPHOLOGY ACCURACY ON REDSHIFT, COLOUR AND MAGNITUDE**

Figs C1–C3 illustrate the evolutions of $N_i$, $|\langle \Delta T_i \rangle|$ and $\sigma_{T_i}$ as a function of spectroscopic redshift $z_{\text{spec}}$, $g-r$ colour and $r$ magnitude in removing catastrophic identifications for models A–D2 (based on the morphological galaxy sample).

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**Figure C1.** Evolutions of $N_i$ (green dotted line), $|\langle \Delta T_i \rangle|$ (black solid lines) and $\sigma_{T_i}$ (red dashed lines) as a function of spectroscopic redshift $z_{\text{spec}}$ in both cases when using $ugriz$ (thin lines) and $F_{\text{UV}}/ugriz$ (thick lines) photometry. In the shaded regions, $N_i \geq 10$.

**Figure C2.** Similar to Fig. C1, but as a function of $g-r$ colour.
Figure C3. Similar to Fig. C1, but as a function of $r$ magnitude.