A Self-consistent Method for Estimating Photometric Redshifts

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Abstract. A new method is developed for estimating photometric redshifts, using realistic template SEDs, extending over four decades in wavelength (i.e. from 0.05 \(\mu\)m to 1 mm). The SEDs are constructed for four different spectral types of galaxies (elliptical, spiral, irregular and star-burst) and satisfy the following characteristics: a). they are optimised to produce the observed colours of galaxies at \(z \sim 0\); b). incorporate the chemo-photometric spectral evolution of galaxies of different types, in agreement with observations; c). allow treatment of dust contribution and its evolution with redshift, consistent with the spectral evolution model; d). include absorption and re-emission of radiation by dust and hence, realistic estimates of the far-infrared radiation; e). include correction for inter-galactic absorption by Lyman continuum and Lyman forest.

Using these template SEDs, the photometric redshifts are estimated to an accuracy of \(\Delta z = 0.11\). The degeneracy in the method and hence, the redshifts and spectral types, are explored via Monte Carlo simulations. The consistency of the technique is demonstrated by estimating photometric redshifts to a UV selected sample of HDF galaxies and investigating if the statistical results (i.e. luminosity densities) are in agreement with other independent studies.

1. Introduction

The subject of photometric redshift measurement (i.e. estimating redshifts to galaxies from multi-waveband photometric observations) has recently been revitalised, due to a rapid increase in the number of existing multi-waveband galaxy surveys. This provides a fast way for estimating redshifts to a large number of galaxies, with some trade-off in their accuracy. Moreover, in the case of faint galaxies (\(I > 25\) mag.), where spectroscopic redshifts are more difficult to measure even with the largest telescopes, photometric redshift technique is the only way to secure their redshifts.

For a given galaxy, the photometric redshift can be estimated by comparing its observed SED with a set of template SEDs, corresponding to different galaxy types and shifted to different redshifts, allowing for the galaxy evolution with
look-back time. The redshift and spectral type associated with the template SED which is the closest to the observed SED will then be assigned to that galaxy. Therefore, the crucial problem is the choice of the template SEDs and their behaviour at high redshifts. There are two general ways for adopting the template SEDs, as discussed below;

a). Empirical templates: in this case one uses the observed SEDs for different types of galaxies. The problem here is that there are not enough information about the SEDs for different classes of galaxies at different redshifts (particularly at high redshifts). Therefore, incorporating the spectral evolution of galaxies to the model SEDs of different types is difficult and uncertain.

b). Synthetic templates: uses model SEDs for different spectral types of galaxies, shifted in redshift space, assuming evolutionary population synthesis (EPS) models. The main problem here is to construct realistic model SEDs at different redshifts by constraining the evolutionary models.

In the present study, we adopt a combined approach to self-consistently model the template SEDs at different redshifts, in agreement with observations. In particular, the effect of dust and its evolution with redshift is included in the SEDs, consistent with the EPS models, and optimised using observations at different look-back times.

2. The Photometric Redshift Technique- A New Approach

A large set of chemo-photometric Evolutionary Population Synthesis (EPS) models with different input parameters are developed, each accounting for both the local properties and evolutionary behavior of different types of galaxies. For a given spectral type of galaxies, the model parameters are normalised to those at $z = 0$, by fitting them to the local observed SED of their respective type. The evolutionary behaviour (i.e. input parameters) of the EPS models (which also include contribution from dust) are then constrained by estimating the photometric redshifts ($z_{\text{phot}}$) to a calibrating sample of 73 galaxies with available spectroscopic redshifts ($z_{\text{spec}}$) and minimising the rms scatter between them. The calibrating sample is adopted from the Hubble Deep Field (HDF) so that the galaxies will have detection in, at least, four passbands, including UV which is crucial for any photometric redshift determination. The procedure is summarised in the flow chart in Figure 1.

The parameters in the EPS models, constrained by observations, consist of the IMF, formation redshift ($z_{\text{form}}$), local star formation rate ($\psi_0$) and the time evolution of the star-formation rate, as parametrised by $n$ (see Figure 1). Once these parameters are constrained, the evolution of the optical depth ($\tau$) is determined directly from the gas metallicity, $Z_{\text{gas}}$, and the fractional mass of gas which takes part in star formation ($f_g$), assuming that the gas-to-dust ratio is proportional to the gas metallicity. For galaxies with $z > 2$ in the calibrating sample, the effect of Lyman continuum and Lyman forest absorption is estimated. The fluxes for these objects are subsequently corrected for inter-galactic absorption before they are used to constrain the EPS models. The template SEDs cover a range in wavelength from 0.05 µm to 1 mm.

The sensitivity of the result to the EPS model parameters are shown in Table 1. The optimum rms scatter obtained on the $z_{\text{phot}}$ vs. $z_{\text{spec}}$ plane (Fig.
Model SEDs (E, Sp, Sb, Irr) [IMF, \psi, f_0, m, Z_{gas}, z_{form}]

Optimized to fit local observed SEDs \{f_\ell(z_\ell), Z_{gas}(z_\ell), m, \psi\}

Optimize model parameters by minimizing \textit{rms} between \textit{zphot} and \textit{zspec}

Estimate \textit{zphot} for galaxies with known \textit{zspec} for given model parameters (IMF, \textit{zform}, etc)

$$f_0 = m_{gas}/m_{phot}$$
$$\psi(t) = \psi_0 f_\ell(t)^n M_\odot yr^{-1}$$
$$\tau(t) \propto Z_{gas} f_0(t)$$

Final Template SEDs for E, Sp, Sb, Irr

$$\textit{rms} = (1/N) \sum \left| z_{phot} - z_{spec} \right|^2$$

Figure 1. Flow chart showing the new procedure for finding template SEDs

2) is 0.11 (model 4 in Table 1), which is found using template SEDs for four different types of galaxies (elliptical, spiral, starburst and irregular) and only four passbands (UVRI). This relation for the calibrating sample is presented in Figure 2, with its \textit{rms} scatter taken as the error in our photometric redshifts.

3. Degeneracy in Photometric Redshifts

A source of uncertainty in estimating the photometric redshifts and spectral types of galaxies is the possibility that the models might be degenerate (i.e. different template SEDs producing the same result). Furthermore, the photometric errors in the observed SEDs are likely to affect the final estimate of both the photometric redshift and the spectral type of their respective galaxy.

To investigate the uniqueness of the photometric redshift solutions in this study, a Monte Carlo simulation is performed. A simulated catalogue is generated to resemble the observed, UV selected HDF survey, with UBVI magnitudes, known redshifts (\textit{zinput}) and spectral types (a UV selected catalogue is used here to ensure the availability of UV data which are crucial for any photometric redshift measurement). The galaxies in this catalogue are randomly selected to have SEDs similar to the synthetic SEDs for any of the four types of galaxies.
Figure 2. $z_{\text{phot}}$ vs. $z_{\text{spec}}$ for the calibration sample of 73 HDF galaxies. Dashed lines correspond to the $3\sigma$ limits.

Table 1. Sensitivity of the $rms$ scatter between the photometric and spectroscopic redshifts on the EPS model parameters (i.e. template SEDs)

| Model | IMF  | $m_f$ | Number of Templates | $z_{\text{form}}$ | $rms$ |
|-------|------|-------|---------------------|-------------------|-------|
|       |      |       | E Sp Sb Irr         |                   |       |
| 1     | Salpeter | 0.01  | 4 5 5 5 1 | 0.18             |
| 2     | "     | 0.01  | 3 5 5 5 – | 0.26             |
| 3     | "     | 0.01  | 3 5 2 5 – | 0.24             |
| 4     | "     | 0.01  | 4 5 2 5 1 | 0.11             |
| 5     | Salpeter | 0.10  | 4 5 5 5 1 | 0.27             |
| 6     | "     | 0.10  | 3 5 5 5 – | 0.38             |
| 7     | "     | 0.10  | 3 5 2 5 – | 0.37             |
| 8     | "     | 0.10  | 4 5 2 5 1 | 0.22             |
| 9     | Scalo | 0.10  | 4 5 5 5 1 | 0.28             |
| 10    | "     | 0.10  | 3 5 5 5 – | 0.52             |
| 11    | "     | 0.10  | 3 5 2 5 – | 0.45             |
| 12    | "     | 0.10  | 4 5 2 5 1 | 0.25             |
Figure 3. $\log \left( \frac{z_{\text{output}}}{z_{\text{input}}} \right)$ results from simulation. The peak at zero indicates that the redshifts in the simulated catalogue are reproduced.

Figure 4. Changes in the UV luminosity densities with redshift, using photometric redshifts for the UV selected HDF survey (filled circles). Compared with estimates from Lilly et al. (1996)-(crosses); Connolly et al. (1998)-(triangles); Madau et al. (1996)-(filled squares).

(E, Sp, Sb, Irr) considered here, shifted in redshift space. Random Gaussian noise, resembling photometric errors are then added to the simulated SEDs. The simulated catalogue contains 273 galaxies (the same as the complete UV-selected HDF catalogue), has a magnitude limit of $U=27$ mag., an apparent UV magnitude distribution similar to the observed catalogue and a redshift limit of $z=2.5$ (maximum redshift allowed in a UV selected survey).

The photometric redshift code was then used to predict the redshifts ($z_{\text{output}}$) and spectral types of individual galaxies in the simulated catalogue and to compare them with their input values. The $\log \left( \frac{z_{\text{output}}}{z_{\text{input}}} \right)$ distribution (Fig. 3) shows a distinct peak at zero, indicating that the redshifts for the simulated galaxies are well reproduced within $\Delta z \sim 0.11$.

As far as the predicted spectral types are concerned, we recover the type classification for ellipticals in the input catalogue by 100% (i.e. no mis-identification of ellipticals). Regarding the spirals, irregulars and starbursts, we can recover, respectively, 79%, 85% and 71% of the spectral types of galaxies in the input catalogue.

4. Consistency Test

In order to explore the consistency of the above procedure, we apply it on a complete sample of UV selected galaxies from the HDF, to estimate their photometric redshifts. Using this redshift catalogue, we then predict the physical
quantities (i.e. the luminosity density) in redshift intervals and compare them with similar measurements from other independent studies. A UV selected survey is particularly useful for such comparison because the UV light is heavily affected by dust in galaxies, allowing a test of the estimated extinction corrections. Moreover, such surveys do not contain objects with $z > 2.5$ and hence, are less affected (then deep surveys in other bands) by uncertainties in correction for Lyman continuum absorption.

The UV luminosity densities are estimated in redshift intervals, using the photometric redshift catalogue. The results are compared with similar measurements from other, independent, studies (Fig. 4) and show excellent agreement. This indicates that the statistical results, based on the present photometric redshift technique, are consistent with other studies.

5. Summary and Conclusion

A new method is presented to estimate photometric redshifts of galaxies. The main improvement in this study is to develop more realistic template SEDs over a large range in redshift and in agreement with the observational data. The SEDs cover a range in wavelength from 0.05 $\mu$m to 1 mm, with their main characteristics as follows: a). they are optimised to produce the observed colours of galaxies at $z \sim 0$; b). incorporate the chemo-photometric evolution of galaxies of different types (i.e. stellar luminosities for different metallicities), in agreement with observations; c). allow a self-consistent treatment of dust contribution and its evolution with redshift; d). include absorption and re-emission of radiation by dust and hence, realistic estimates of the far-infrared radiation; e). include correction for inter-galactic absorption by Lyman continuum and Lyman forest.

Using a calibration sample of 73 galaxies with available spectroscopic redshifts, the evolutionary model parameters are optimised to get the minimum scatter between the photometric and spectroscopic redshifts in the calibrating sample. Using four passbands (UVRI), the photometric redshifts are estimated to an accuracy of $\Delta z = 0.11$.

The method is applied to a UV selected sample of HDF galaxies. The UV luminosity densities, estimated in redshift intervals, are in excellent agreement with similar measurements from other, independent, surveys.

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