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Constraining galaxy evolution and cosmology from high-redshift galaxy ages

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Abstract. We present here a work focused on both cosmology and galaxy evolution. First, we use both photometry and spectroscopy to compute galactic ages and their formation redshift. This allows to determine the epoch of galaxy formation and its duration. Then, we use the time evolution of the 4000 Å break to compute ages of passively evolving galaxies. From these ages we compute the Hubble parameter evolution.

Keywords : High redshift galaxies, galaxy evolution, cosmology

1. Introduction

The evolution of the physical properties of galaxies with cosmic time has become a major question in Astrophysics. This characterization of this properties is made possible thanks to stellar population synthesis models like the ones developed by Bruzual & Charlot (2003) or Maraston (2005 & 2011). From these models we can compute several parameters such as stellar mass, star formation rate and ages (among others). While stellar masses and average star formation rates are the most widely used parameters, the knowledge of galaxy ages can also bring important constraints on galaxy evolution and cosmology. Here we present three methods of galaxy age determination, based on the usage of spectral energy distribution (SED) and spectroscopic fitting, and specific spectral features evolution. In Section 4, we present the Galaxy Observed-Simulated SED Interactive Program (GOSSIP) which allows to take into account both the spectroscopy and the photometry during the same fitting procedure.

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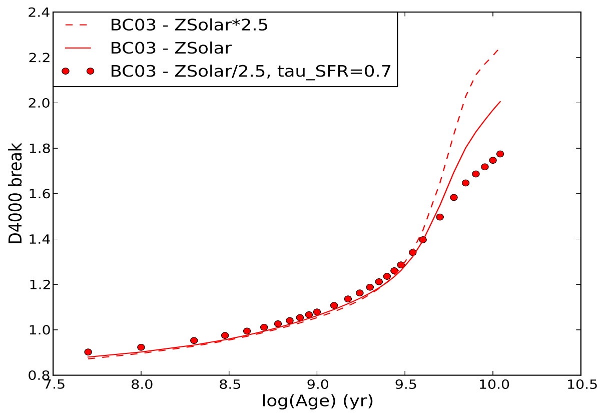

Figure 1. Different methods of galaxy dating. This plot represents the evolution of the D4000 amplitude for three metallicities (solar, half-solar and twice solar) from the BC03 model. We used exponentially declining star formation history with a timescale parameter of 0.7 Gyr.

We focus on constraints derived from galaxy ages on the galaxy formation epoch and the Hubble parameter evolution using high redshift spectroscopic surveys: the Vimos VLT Deep Survey (VVDS Le Fèvre et al., 2013) and the Vimos Ultra Deep Survey (VUDS).

2. Galaxy ages estimation

Galaxy dating is a powerful tool in astrophysics. Computing the ages of a galaxies is not an easy task. It suffers from numerous degeneracies as the age-metallicity degeneracy or the dust-age degeneracy.

Three methods are used to estimate ages. The most commonly used is the SED-fitting. It is based on synthetic templates fitted to the observed photometry. The second method uses the same approach as SED-fitting but on spectra. It is the spectroscopic fitting. Since the spectroscopy brings more data points (up to 1000 for this work) than the photometry (10 for this work), the spectral fitting is more time consuming.

The last method of estimation of galactic ages makes use of the time evolution of specific age-sensitive spectral features. For example the Fig. 1 represents the evolution of the 4000 Å break (D4000) as a function of time. This index has been defined as the ratio of the mean flux in a red band (4050 – 4250 Å) and in a blue band (3750 – 3950 Å) (Bruzual 1983). It is due to an accumulation of metallic lines. This plot shows that for a given D4000 it is possible to date the observed galaxy.

3. Observations

We make use of two surveys, VVDS and VUDS. The VVDS (VVDS Le Fèvre et al, 2013) is a survey of 35000 galaxies with spectroscopic redshifts from $z = 0$ to $z = 6.7$. It is composed of three surveys; the VVDS-wide, covering an area of 8.7 deg^2 and with 25805 spectroscopic redshifts down to $i_{AB} = 22.5$; the VVDS-Deep survey covers an area of 0.74 deg^2 where 11486 galaxies have been observed with i_{AB} down to 24 and the VVDS-Udeep, which has observed 938 galaxies in an area of 512 arcmin^2 with $23 < i_{AB} < 24.75$. Moreover, during the observations 422 AGN and 217 Lyman alpha emitters have been detected.

The VUDS (for Vimos Ultra Deep Survey) is an on-going spectroscopic survey of 10000 star forming galaxies with spectroscopic redshifts $2 < z < 6+$. Galaxies are selected using deep multi-band photometry in a total area of 1 deg^2 from the COSMOS, VVDS-2h and ECDFS fields. Selected objects are observed with the Vimos spectrograph and 14h integration time with a wavelength coverage from 3600 to 9500 Å.

4. The GOSSIP+ tool: Spectral-SED fitting

GOSSIP is a tool dedicated to the fitting of both spectroscopy and photometry. It has been initially developed by P. Franzetti and M. Scodeggio in Milan, in order to be used for spectroscopic galaxy redshift surveys like the VVDS survey. It allows the combination of magnitudes in several bands and of a spectrum to perform a χ^2 minimization fitting versus a set of galaxy templates, either produced from synthetic stellar population models or from observations (Thomas et al., in preparation). The result of the fit can be used to estimate several parameters like the star formation rate, the age and the mass of the observed galaxy thanks to their Probability Distribution Function (PDF). We updated GOSSIP by adding new functionnalities and by modifying pre-existing functions. The two main new functions are: the template builder and the intergalactic medium extinction (IGM) implementation.

The former allows to costruct a library of composite stellar population (CSP) from Bruzual & Charlot (2003) or Maraston (2005, 2011) single stellar populations (SSP) models. This builder works as follows. From a SSP with given metallicity and resolution, a star formation history (SFH) is applied. This SFH can be either exponentially declining or exponentially delayed. Then, a list of ages at which the CSP will be computed have is given. Finally the Interstellar Medium (ISM) extinction is computed from the Calzetti's law (Calzetti 2001). The resulting templates can then be used for the fitting. Another main feature that has been implemented in GOSSIP is the IGM attenuation. The light coming from a distant galaxy travels through numerous clouds. These clouds are responsible of absorption features in the spectra of those objects. We use the IGM extinction curves produced by Meiksin (2005).

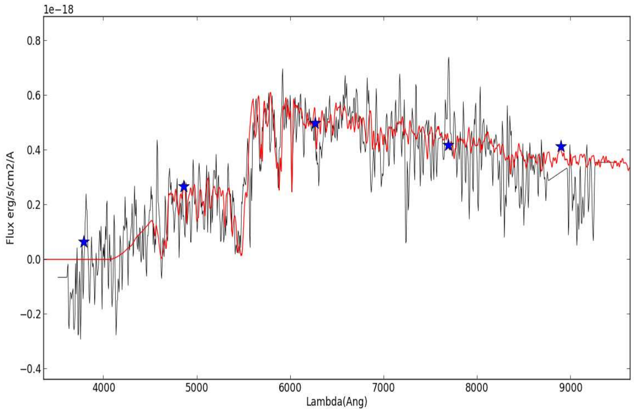

Figure 2. Spectroscopic-SED fitting of an object at redshift $z = 3.5038$. The black line is the observed spectrum, the blue stars are the magnitude points and the red line is the best-fit template.

The implementation of these two functions allows the fitting of very high redshift galaxies. The Fig. 2 shows a fit of both the spectroscopy and the photometry of a galaxy at redshift $z = 3.5038$ produced by GOSSIP+.

It is interesting to note that the higher is the redshift, the weaker are the degeneracies. Indeed, at very high redshift the set of allowed ages are strongly limited by the age of the universe. At high redshift $z > 2 - 3$ the age-metallicity degeneracy can be broken when the known age constraint from the age of the universe is taken into account.

5. Epoch of galaxy formation

The aim of galaxy dating is to estimate when the epoch of galaxy formation took place as well as its duration.

Some previous work have tried to answer directly, or indirectly, to these questions. For example Jimenez et al. (2001) used an analytical model to reproduce photometric features of galaxies from which they deduced a distribution of formation redshifts. They found a primary event of galaxy formation at $z \sim 5$ and a secondary event of galaxy formation at $1 < z < 2$. Recently Kaviraj et al. (2013) computed the formation redshift of 330 $1.3 < z < 3$ galaxies and found a peak of formation around $z = 3$.

Below, we present the preliminary results obtained using VVDS galaxies up to $z = 1.3$.

5.1 Selection of the galaxies

We applied two selection criteria on the VVDS-Deep galaxies. Because of the lack of prominent continuum or absorption line features, SED and spectrum fitting have difficulties to handle flat spectra. Therefore we used a criterion on the D4000. This prominent feature stabilizes SED and spectral fitting with well defined PDFs. We have selected objects with $D4000 - 1\sigma > 1.2$. In order to keep only galaxies with good quality spectro-photometry, we impose a match between spectroscopy and photometry. we first normalized the observed spectrum flux to the i-band magnitude and we imposed that the flux ratio between the observed photometric points on the SED and the spectrum do not differ by more than 15% to avoid catastrophic errors in either measurement. From these two criteria our sample is composed of $\sim$ 800 galaxies.

5.2 Results

To compute the formation redshift of all the selected galaxies we performed a fit with GOSSIP+ to get the age and derive the formation redshift.

Table 1. Parameters used to compute ages.

Parameter	SFH exponentially delayed	SFH exponentially declining
IMF	Salpeter	Salpeter
E(B-V)	from 0 to 0.5	from 0 to 0.5
SFH timescale (Gyr)	from 0.1 to 1.5	from 0.1 to 3
Ages (Gyr)	from 0.1 to 14	from 0.1 to 14

We use two libraries, with two models of SSPs, BC03 and M11. The parameters are described in table 1. The metallicity coverage of those two SSP models are $1/50 < Z/Z_\odot < 2.5$ and $1/2 < Z/Z_\odot < 2$, for BC03 and M11, respectively. Since we have selected galaxies with high D4000 break the lack of low metallicity in the M11 models does not affect the results. Indeed the fitting of all these galaxies have shown that the values of metallicity where are order solar. The ages which are computed correspond to the time since the onset of star formation.

Using the ages, formation redshifts (z_f) can be computed and their distribution is shown in Fig. 3. In the left panel we show the results for exponentially declining SFH ($SFR(t) \propto \exp(-t/\tau)$) library and in the right panel we represent the results obtained with the exponentially delayed SFH ($SFR(t) \propto t/\tau^2 \times \exp(-t/\tau)$) library.

It can be seen that the differences between Maraston and BC03 models are not significant. In each case we observe a single peak of galaxy formation around $z = 1.1$. The distribution of z_f for our sample ranges from $z \sim 0.5$ to $z \sim 6$ or more. For

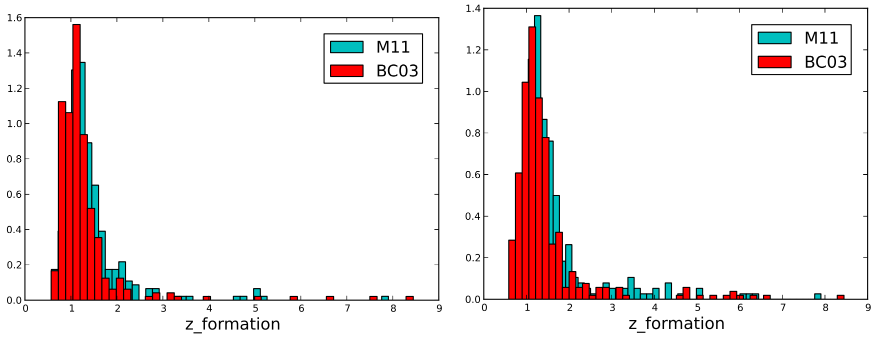

Figure 3. Formation redshift distributions.Left panel: formation redshift distributions using exponentially declining SFH from BC03 (red) and M11 (blue) models. Right panel: formation redshift distributions using exponentially delayed SFH.

exponentially declining SFH the median redshift is $z_f = 1.2$. Moreover there are less galaxies with very high formation redshift $z_f > 2$. While for exponentially delayed SFH, the high formation redshift tail is more populated and extends to higher redshift with a median redshift of $z = 1.6$.

With the VUDS survey it will be possible to populate this tail with $2 < z < 6$ galaxies (Thomas et al. in preparation). This will lead to new constraints on the duration of the epoch of galaxy formation.

6. Cosmological implications

Understanding the nature and the behaviour of dark energy is one of the challenges of modern cosmology. Constraints on cosmological models have been derived from several observables. For example the latest Cosmic Microwave Background (CMB) results from the Planck mission (Ade et al., 2013), the Type Ia Supernovae observation (Riess et al., 1998) which showed that the expansion of the universe is accelerating or the study of gravitational Lensing (Wang et al., 2002). All of these observations agree that the universe is dominated by dark energy with negative pressure. Numerous models have been created to explain this dark energy. The Λ-CDM model (Lambda Cold Dark Matter) is the model commonly accepted in cosmology. In this framework the dark energy is represented by the cosmological constant where the dark energy equation of state is $w = -1$. Other models exist like quintessence models where the dark energy equation of state is redshift-dependant.

Testing these models can be performed in a number of ways, including galaxy dating. Indeed, as revisited recently by Moresco et al. (2012), the use of passively evolving galaxies can provide measurements of the Hubble parameter evolution independently of the cosmology.

6.1 Galaxy selection

The strongest constraints on $H(z)$ are placed from the identification of the oldest galaxies at any redshift. These galaxies are typically massive and non star forming. To select them we use three criteria. First, we use a color-color selection based on NUV, r and J absolute magnitude (Ilbert et al., 2011) to divide the original galaxy sample into three subsamples, depending on their star formation activity: high activity, intermediate activity and quiescent galaxies. We also exclude the galaxies with ongoing star formation by imposing $EW([\mathrm{OII}]) < 5$ Å and $EW(H\alpha) < 5$ Å. To select the most massive galaxies we use a third criterion, $M > 10^{10.6} M_{\odot}$. This combination of criteria leads to the selection of 154 passively evolving galaxies from the VVDS-Deep survey with redshift between $0.4 < z < 1.4$.

6.2 Hubble parameter evolution

To measure the Hubble parameter we use the D4000 break which is an age-sensitive spectral features. As shown in section 2 (Fig. 1) the evolution of that indice is related to the age of the galaxy. Therefore it becomes possible to compute $H(z)$. In the D4000 regime considered here we can approximate the relation between age and the D4000 break as $\Delta D4000 = A(Z, SFH) \times \Delta\mathrm{Age}$. Where $A(Z, SFH)$ is the slope which depends on the metallicity and the star formation history. Consequently the Hubble parameter originally given by $H(z) = (-1/1 + z)(dz/dt)$ becomes

$$H(z) = \frac{-A(Z, SFH)}{(1+z)} \frac{dz}{dD4000}. \tag{1}$$

Our measurements of the Hubble parameter are shown in Fig. 4. We compare our measurements (in red) to those of Moresco et al. (2012; green and blue). We can see that our estimations are fully consistent with those computed by Moresco. Nevertheless, we find that our results are highly sensitive to the mass selection of the sample, and this requires further investigations.

When the VUDS survey will be completed, we will be able to extend this analysis to higher redshift. Sice the D4000 break is not available beyond $z \sim 1.4$ we will use other spectral features as the MG_{UV} feature defined in Daddi et al. (2005).

7. Conclusion and perspectives

In this paper we have pointed out that the age of galaxies is an important parameter for Cosmology and galaxy evolution. This parameter can be estimated from three different methods; the SED-fitting, the spectroscopic fitting and the time evolution of spectral features. We have shown, using the VVDS survey and the GOSSIP tool, two different applications of galaxy dating. The epoch of galaxy formation and the

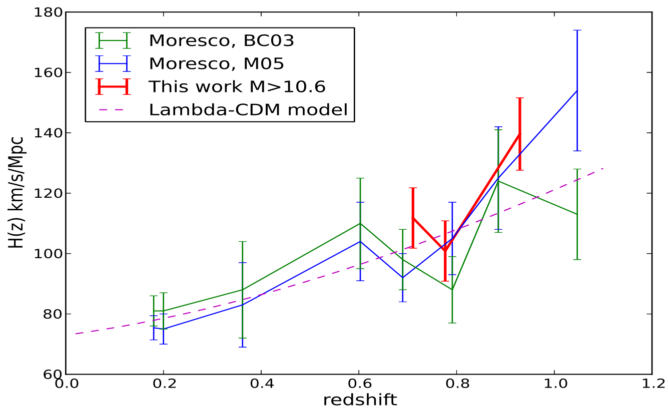

Figure 4. Estimation of the Hubble parameter from our sample of passively evolving galaxies. Comparison with previous studies. The points in green and blue have been computed by Moresco et al. (2012) with the BC03 and M05 models, respectively. The red points represent our estimations. The dashed line corresponds to the Λ-CDM model.

evolution of the Hubble constant. The former showed a peak of galaxy formation at $z \sim 1.5$ and a tail of galaxy formation which goes at $z > 6$. The latter have been computed using passively evolving galaxies and is consistent, within the error bars, with the Λ-CDM model. When the Vimos Ultra Deep Survey will be completed, it will be possible to extend these studies to very high redshifts and set new constraints on both fields. To do so we will need improved SSP models, particularly with a better spectral resolution in the UV between 912 and 2000 Å. As the observed spectra of distant galaxies are mostly UV rest-frame, UV age sensitive indicators have to be used, like the MG_{UV} feature, combined with adapted galaxy selection criteria.

Acknowledgements

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