Old age and supersolar metallicity in a massive $z \sim 1.4$ early-type galaxy from VLT/X-Shooter spectroscopy

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ABSTRACT
We present the first estimate of age, stellar metallicity and chemical abundance ratios, for an individual early-type galaxy at high-redshift ($z = 1.426$) in the COSMOS (Cosmological Evolution Survey) field. Our analysis is based on observations obtained with the X-Shooter instrument at the Very Large Telescope (VLT), which cover the visual and near-infrared spectrum at high ($R > 5000$) spectral resolution. We measure the values of several spectral absorptions tracing chemical species, in particular magnesium and iron, besides determining the age-sensitive D4000 break. We compare the measured indices to stellar population models, finding good agreement. We find that our target is an old ($t > 3$ Gyr), high-metallicity ($[Z/H] > 0.5$) galaxy which formed its stars at $z_{\text{form}} > 5$ within a short time-scale $\sim 0.1$ Gyr, as testified by the strong $[\alpha/Fe]$ ratio ($> 0.4$), and has passively evolved in the first $> 3–4$ Gyr of its life. We have verified that this result is robust against the choice and number of fitted spectral features, and stellar population model. The result of an old age and high-metallicity has important implications for galaxy formation and evolution confirming an early and rapid formation of the most massive galaxies in the Universe.

Key words: galaxies: elliptical and lenticular, cD – galaxies: high-redshift – galaxies: stellar content.

1 INTRODUCTION
The cosmic history of galaxy mass assembly represents one of the open key questions in cosmology. Early-type galaxies (ETGs) are the most effective probes to investigate this topic, as they are the most massive and oldest galaxies in the local Universe and most likely those whose stars formed earliest. Observations have shown that a population of massive and passive galaxies is already in place at high redshift, when the Universe was only a few Gyr old (Cimatti et al. 2004; Saracco et al. 2005). So far, the main physical parameters related to their formation and assembly have been mainly estimated on local ETGs, and their ageing and evolution can mix up and confuse the original properties when the bulk of their mass formed and assembled. Information on the star formation (SF) time-scale of high-$z$ ETGs can be obtained from the detailed chemical abundance ratios of their stellar populations (Thomas, Maraston & Bender 2005), which can be derived by a detailed spectral analysis. Indeed, the abundance of Iron with respect to $\alpha$-elements is tightly correlated with the time delay between Type I and Type II supernovae (SN), giving a direct probe of the time-scale within which SF has occurred.

Up to now, only few works have experimented a spectral analysis on ETGs at $z > 1$ (Onodera et al. 2012; Jørgensen et al. 2014; Lonoce et al. 2014) due to the low S/N of the available spectroscopic data, and they were mostly focused on age estimates, in particular using...
the $UV$ region (Cimatti et al. 2008). The analysis of the rest-frame optical spectrum is still lacking.

Furthermore, measures are usually performed on stacked spectra (Onodera et al. 2015), thus deleting possible peculiarities of single objects.

A single-object measurement of age, stellar metallicity and chemical abundance ratios of $z > 1.2$ ETGs is missing at the present time. We fill this gap, presenting the first attempt to measure the detailed chemical composition, besides age, of a $z \sim 1.4$ ETG directly in the early stages of its evolution.

Throughout this paper, we assume a standard cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. 

2 COSMOS-307881: SPECTROSCOPIC DATA

Our target is a bright and massive ($> 10^{11} M_\odot$) ETG from the K-selected galaxy catalogue in the COSMOS (Cosmological Evolution Survey) field (McCracken et al. 2010). It is one of the 12 galaxies with $K_s$(Vega) <17.7 selected by Mancini et al. (2010) on the basis of three criteria: (i) non-detection at 24 $\mu$m in Table 1. For further details see Mancini et al. (2010) and Onodera et al. (2015). All available information are shown in comparison with the photometric points (cyan diamonds, second panel). The reduced mono-dimensional spectrum of 307881 (black line) is overlaid by the $H\beta$ and Mg$b$ emission line. We can exclude that its origin is due to an active AGN, since we do not see any other signature in the line (Fig. 1, middle panel). We can exclude that its origin is due to an active AGN, since we do not see any other signature in the line (Fig. 1, middle panel). We can exclude that its origin is due to an active AGN, since we do not see any other signature in the line (Fig. 1, middle panel).

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3 SPECTRAL ANALYSIS

As a first step, we measured the redshift of 307881 fitting the $Mg_b$ line region, which is the cleanest from the background residuals, as it can be seen in Fig. 1 (bottom panel), finding $z = 1.426 \pm 0.001$. The $Mg_b$ line region has been also used to find a best-fitting velocity dispersion estimate, that resulted to be $\sigma = 385 \pm 85$ km/s. More details on the fitting procedure adopted to fix both $z$ and $\sigma$ will be described in the forthcoming paper.

We then selected some indices whose absorption features are clearly visible in the observed spectrum, to try to simultaneously derive both the mean age and the metallicity of its stellar population. The selected indices are: D4000 index (Hamilton 1985), $H_\gamma$ (Worthey & Ottaviani 1997), G4300, Fe5433, Ca4227, Mg$b$, H$\beta$, Fe5015 and Mg$b$ (Lick/IDS system, Worthey et al. 1994). In particular, it is well known that the Mg$b$ index is the best metallicity and chemical abundance dependent index in the region around 5000 Å restframe (Korn, Maraston & Thomas 2005). In Table 2 we report the measured values of these indices together with their errors derived by means of Monte Carlo simulations set on the uncertainties in the flux measurements.

Finally, we want to point out the presence of the [OIII]3727 emission line (Fig. 1, middle panel). We can exclude that its origin is due to an active AGN, since we do not see any other signature in the observed wide spectral window. There are reasonable possibilities that this emission is caused by the UV ionizing emission of old stars in post-main-sequence phases (Yi & Yoon 2004), as confirmed by UV indices (Loncone et al., in preparation), while a strong contribution from SF can be excluded. Indeed, as it can be noted from Fig. 2 (left-hand panels), it is highly unlikely that the $H\beta$ feature is affected by emission, considering also that its value suggests a stellar population age in good agreement with that derived by the $H_\gamma$ and D4000 index.

4 MODEL COMPARISON

In Fig. 3 we show the observed Mg$b$ and $H\beta$ indices (blue diamond), compared to the predictions of the SSP of Thomas et al. (2011; hereafter TMJ models), based on the MILES library for a wide range of ages (from 0.1 Gyr shown up to the age of the Universe at $z \sim 1.4$, i.e. 4 Gyr); supersolar metallicities $[Z/H] = 0.35$ (red lines) and $[Z/H] = 0.67$ (cyan lines), and various $\alpha$/Fe parameters, namely $[\alpha/Fe] = 0.0, 0.3, 0.5$. Models assume a Salpeter (1955) initial mass
Figure 1. COSMOS 307881. The galaxy observed spectrum (black line) is compared to a model (Maraston & Strömbäck 2011) with age of 4 Gyr and supersolar metallicity ($Z = 0.04$), and to observed photometric data (cyan diamond). Top panel: VIS and NIR spectral region together with the HST/ACS $I$-band image of the target. Middle panel: zoom of the 4000 Å rest-frame region. Bottom panel: zoom of the 5000 Å rest-frame region. The main absorption (and one emission) lines in each spectral region are highlighted. Dark green lines indicate the residual spectrum.
Table 1. COSMOS-307881. Data derived from the analysis of Onodera et al. (2012): K-band magnitude in Vega system ($K_s$); spectroscopic redshift ($z_{\text{spec}}^{\text{ONOD}}$); stellar population age ($\text{Age}_{\text{phot}}$) and logarithm of the stellar mass ($\log \mathcal{M}_\ast$) derived from SED fitting assuming a Chabrier IMF (Chabrier 2003); effective radius ($R_e$); degree of compactness ($C = R_e/R_{e,z = 0}$); Sérsic index ($n$). Units of right ascension are hour, minutes and seconds, and units of declination are degrees, arcminutes and arcseconds.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>DEC</th>
<th>$K_s$ (Vega)</th>
<th>$z_{\text{spec}}^{\text{ONOD}}$ (*)</th>
<th>$\text{Age}_{\text{phot}}$ (Gyr)</th>
<th>$\log \mathcal{M}<em>\ast$ (M$</em>\odot$)</th>
<th>$R_e$ (kpc)</th>
<th>$C$</th>
<th>Sérsic $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>307881</td>
<td>10:02:35.64</td>
<td>02:09:14.36</td>
<td>17.59</td>
<td>1.4290 ± 0.0009</td>
<td>3.50</td>
<td>11.50</td>
<td>2.68 ± 0.12</td>
<td>0.32</td>
<td>2.29 ± 0.10</td>
</tr>
</tbody>
</table>

Note. (*) This work: $z_{\text{spec}} = 1.426 ± 0.001$.

Figure 2. H\$\beta\$ (left-hand panels) and Mg\$b\$ (right-hand panels) features in the 4 Gyr, 2 Z\$\odot\$ metallicity model shown in Fig. 1. From top to bottom we show: model at $z \sim 1.4$; model corrected for $\sigma = 385$ km/s; model downgraded for the observed Poissonian noise; model compared to the observed spectrum (point-dashed red line).

Table 2. Measured indices values.

<table>
<thead>
<tr>
<th>Index</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4000</td>
<td>2.44 ± 0.12</td>
</tr>
<tr>
<td>D$_\gamma$4000</td>
<td>2.42 ± 0.17</td>
</tr>
<tr>
<td>H$\gamma$/F</td>
<td>-1.56 ± 0.92</td>
</tr>
<tr>
<td>G4300</td>
<td>6.52 ± 1.12</td>
</tr>
<tr>
<td>Fe4383</td>
<td>7.40 ± 1.74</td>
</tr>
<tr>
<td>Ca4455</td>
<td>1.06 ± 0.83</td>
</tr>
<tr>
<td>Fe4531</td>
<td>3.20 ± 1.40</td>
</tr>
<tr>
<td>H$\beta$</td>
<td>2.52 ± 0.93</td>
</tr>
<tr>
<td>Fe5015</td>
<td>3.89 ± 1.91</td>
</tr>
<tr>
<td>Mg$\beta$</td>
<td>5.75 ± 0.81</td>
</tr>
</tbody>
</table>

function (IMF), and are corrected for the measured velocity dispersion value of $\sigma = 385 \pm 85$ km/s. As it can be seen, the extreme value of the Mg$\beta$ index fully requires high-metallicity models up to $[Z/H] = 0.67$. In particular, in Fig. 3 the model expectations for these indices are reported also in case of non-solar values of the $\alpha$-enhancement [$\alpha$/Fe], from 0.3 to 0.5 (dashed and dotted lines, respectively).

Figure 3. H\$\beta\$ versus Mg\$b\$ plot. Comparison between the measured indices (blue diamond) and models of Thomas et al. (2011) (lines). Ages run from 0.1 to 4 Gyr, for super solar metallicities of $[Z/H] = 0.35, 0.67$ (red, cyan lines), and $\alpha$-element abundances: $[\alpha$/Fe] = 0.0, 0.3, 0.5 (solid, dashed, dotted lines). The models are corrected for the measured value of $\sigma = 385$ km/s.
Models corresponding to extreme values of $[\alpha/\text{Fe}]$>0.5 seem to be required to match the observations.

The behaviour of the Mg b index, requiring such extreme values of Z, is confirmed also when considering the other absorption lines that we were able to measure on this X-Shooter spectrum. Indeed, as it can be noticed in Fig. 4 where we propose three examples of Lick indices (G3400, Hβ, and Fe4383, upper, middle and bottom panel, respectively) as a function of D4000, all measured indices consistently point towards a very-high metallicity ($[\text{Z}/\text{H}] \sim 0.67$, cyan lines) being only marginally consistent with the 2 $Z_{\odot}$ values ($[\text{Z}/\text{H}] \sim 0.35$, red lines).

Notice that the highest metallicity models in Thomas et al. (2011) are partly in extrapolation, as they are sampling the edge of the parameter space in terms of the available empirical fitting functions for such extreme stellar parameters (see Johansson, Thomas & Maraston 2010). At the same time, the underlying stellar tracks are based on real calculations (see Maraston et al. 2003, for details).

More quantitatively, we have computed the best-fitting solution obtained comparing all 9 observed indices values (Table 2) with models. The free parameters were age (0.1–4.5 Gyr, truncated at the age of Universe, with step 0.1 Gyr), the total metallicity

\[ \sigma = 385 \text{ km/s} \]

(from $[\text{Z}/\text{H}]$=−2.25 to $[\text{Z}/\text{H}]$ = 0.67, with step 0.01) and the $\alpha$/Fe-enhancement (from [α/Fe] =−0.3 to [α/Fe] = 0.5, with step 0.01). The minimum $\chi^2$ value corresponds to an age of 4.04±0.2 Gyr, metallicity $[\text{Z}/\text{H}] = 0.61_{-0.06}^{+0.06}$ and $[\alpha/\text{Fe}] = 0.45_{-0.09}^{+0.05}$ with $\chi^2 = 0.7$ and an associated probability ∼70 per cent. Errors indicate the range values of these parameters over all the solutions associated with probabilities larger than 65 per cent. The distributions of the three fitting parameters, displayed in different $\chi^2$ ranges, are shown in Fig. 5, top panel. A global picture of the $\chi^2$ values can be seen in Fig. 6 where the minimum $\chi^2$ trends of the three parameters of all solutions are shown. It is easy to notice that ages ≤2 Gyr can be completely excluded due to the rapid increasing of their $\chi^2$ values towards younger ages. Instead for ages ≥4.5 Gyr (limit of the Universe age, not shown here) the $\chi^2$ values remains practically constant.

Furthermore, we found that models with $Z \leq Z_{\odot}$ provide a fit of the free parameters with a probability less than 0.1 per cent.

We also verified the strength of this result by repeating the same fitting process selecting smaller and different set of indices, finding very similar solutions with respect to the previous ones based on the whole set of indices. Two examples are shown in Fig. 5 (middle and bottom panels): the distributions of the fitting solutions are obtained from two smaller sets of indices (i) D4000, G4300, Hγ, Fe4383, Hβ, Fe5015 and Mg b, and (ii) D4000, Hγ, Hβ and Mg b which lead to a best-fitting solution of (i) age = 4.0 Gyr, $[\text{Z}/\text{H}] = 0.61$ and $[\alpha/\text{Fe}] = 0.44$ with $\chi^2 = 0.9$, and (ii) age = 4.0 Gyr, $[\text{Z}/\text{H}] = 0.60$ and $[\alpha/\text{Fe}] = 0.5$ with $\chi^2 = 0.5$, both totally consistent with the all-indices one.

We also evaluated the feasibility of this analysis on this low S/N spectrum, in particular for metallicity and $\alpha$-enhancement estimates, by repeating it on a set of 500 mock spectra built on a model spectrum with parameters as the best fit to the observed one (cf. Table 3) and downgraded with the Poissonian observed noise. The obtained distributions of the measured $[\text{Z}/\text{H}]$ and $[\alpha/\text{Fe}]$ are shown in Fig. 7. They all peak around the true original values (red vertical lines) demonstrating that within the declared errors the obtained values are solid.

Furthermore we tested if the large error on the velocity dispersion could affect the results by performing the same analysis assuming $\sigma = 300$ km/s. We found the same best-fitting solution (4.1 Gyr, $[\text{Z}/\text{H}] = 0.6$, $[\alpha/\text{Fe}] = 0.41$ with $\chi^2 = 0.6$).

Finally, in order to test the model dependence of this result, we repeated the same analysis adopting the Bruzual & Charlot (2003) models (BC03). These models do not include the $[\alpha/\text{Fe}]$ parameter, hence we shall use them to constrain age and total metallicity solely. The BC03 models cover a slightly lower Z range with respect to our fiducial TMJ models, and are based on different stellar evolutionary tracks. The BC03 best-fit corresponds to an age of 4.5 Gyr and a metallicity of $[\text{Z}/\text{H}] = 0.4$, which is the maximum available metallicity in these models. Hence our result of a high-age and high-Z is not model dependant.

It is important to note the high metallicity is mainly derived as a consequence of the maximum allowed age of 4.5 Gyr. Should we allow the age to be older than the age of the Universe, the metallicity will decrease, as a result of age/metallicity degeneracy. Actually, the large error bar of both the indices and of $\sigma$ prevents a real precise measure of the metallicity, but the peculiarity of such a strong Mg b absorption band combined with the narrow range of possible ages (due to its redshift), make necessary the assumption of a very high value of the stellar metallicity.
Supersolar metallicity of a massive $z \sim 1.4$ ETG

Figure 5. Distributions of the fitting-solutions: age, metallicity and $\alpha$-enhancement. Colours and symbols indicate solutions in different $\chi^2$ ranges, e.g. green squares include the most probable solutions. Top panel: distributions obtained from the all-indices analysis; middle panel: distributions obtained from a smaller set of indices: D4000, G4300, H$_\gamma$, Fe4383, H$_\beta$, Fe5015 and Mg$b$; bottom panel: distributions obtained from a smaller set of indices: D4000, H$_\gamma$, H$_\beta$ and Mg$b$.

Figure 6. Trends of minimum $\chi^2$ for age, [Z/H] and [$\alpha$/Fe] of all obtained solutions. In particular, ages <2 Gyr can be completely excluded due to the rapid degrade of $\chi^2$ towards younger ages.

5 DISCUSSION AND CONCLUSIONS

We have performed a detailed spectroscopic analysis of a $z=1.426$, massive ($M^* \sim 10^{11} M_\odot$), early-type galaxy. We gain strong evidence of a high-stellar metallicity and $\alpha$-enhancement, and old (relative to its redshift) age (Table 3). These quantities constrain the past SF history experienced by the galaxy. In particular, the [$\alpha$/Fe] ratio, quantifying the time delay between Type II SN events, responsible of the production of $\alpha$-elements, and the Type Ia SNe, related to the formation of Fe-peak elements, allows us to determine the SF time-scale (Thomas et al. 2005). The high value [$\alpha$/Fe] $\sim 0.4$ obtained for 307881 is a direct signature that its SF time-scale
must have been short. In particular, adopting the simple theoretical
modelling of Thomas et al. (2005), where the SF is modelled with
a Gaussian function, we obtain a time-scale $\Delta t \sim 0.1$ Gyr covering
the interval within which 95 per cent of the stars were formed.
Considering also the old age of its stellar content, this suggests that
307881 formed the bulk of its stars at $z_{\text{form}} > 5$ within a short time-
scale of $\Delta t \sim 0.1$ Gyr and then passively evolved over the following
4 Gyr.

With the high [$\alpha$/Fe] value suggesting a short SF time-scale for
307881, the clear indication for an extremely high total metallicity
opens new issues on the gas enrichment history of the Universe. It is
worth emphasizing that the global integrated metallicity of the
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### Table 3

<table>
<thead>
<tr>
<th>$z_{\text{spec}}$</th>
<th>$\sigma$ (km/s)</th>
<th>Age (Gyr)</th>
<th>[Z/H]</th>
<th>[$\alpha$/Fe]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.426 ± 0.001</td>
<td>385 ± 85</td>
<td>4.0 ± 0.5</td>
<td>0.61 ± 0.06</td>
<td>0.45 ± 0.05</td>
</tr>
</tbody>
</table>

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