Pushing the VLT Spectroscopy of Distant Galaxies to the Limits and Future Prospects

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1 Introduction

The aim of this paper is to illustrate a key scientific case in the field of galaxy formation and evolution which is relevant to highlight the current limits of 8m-class telescopes and discuss the prospects of future VLT and E-ELT instrumentation.

The science case concerns the evolution of early-type galaxies (ETGs) (i.e. the ellipticals and lenticulars, E/S0). ETGs play a crucial role in cosmology. They are the most massive galaxies in the local Universe, contain most of the stellar mass and are primary probes to investigate the cosmic history and the physics of galaxy mass assembly. ETGs are also fundamental in tracing the evolution of the large scale structure and the co-evolution of spheroids and their central supermassive black holes. Although ETGs in the present-day Universe are rather simple and homogeneous systems in terms of morphology, colors, stellar population content and scaling relations [30], their formation and evolution is still a debated question.

The most recent surveys suggest the most massive ETGs (stellar mass $> 10^{11}$ $M_\odot$) were already in place at $z \approx 0.7$–0.8, with a number density consistent with the one at $z = 0$ whereas the evolution is more pronounced for the lower mass ETGs which may increase their mass from $z \approx 0.7$–0.8 to $z = 0$ through the merging of disk and/or ETGs (e.g. [3, 5, 6, 9, 17, 28, 29, 33, 37]). This mass-dependent evolution is known as "downsizing" [12], i.e. with massive galaxies forming their stars earlier and faster than the low mass ones. It is unclear whether the downsizing can be extended to the stellar mass assembly evolution itself [6, 9] and if this may represent a significant problem for galaxy formation models where massive galaxies are expected to assemble their mass more gradually through hierarchical merging of CDM halos [14].

Beyond $z \approx 1$ the picture is even more controversial because the spectroscopic identification and study of ETGs at these redshifts is often beyond the capabilities of 8m-class telescopes. ETGs have absorption line spectra and the most prominent spectral features (e.g. the D4000 continuum break and CaII H&K absorption lines) are redshifted at $\lambda > 0.8$–1 μm for $z > 1$–1.5, where ground-based spectroscopy is increasingly difficult due to the intense OH sky lines and telluric absorptions. Moreover, due to the strong k-correction, ETGs become rapidly very faint at $z > 1$ (e.g.

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$I > 24$, $K > 21$, AB) and it is extremely difficult to obtain high quality continuum spectroscopy either in the optical or near-infrared.

Pushing the 8m-class telescopes to their limits, it has been possible to unveil some ETGs up to $z \approx 2$ with deep spectroscopy done either in the optical [8, 10, 13, 24] or in the near-IR [20, 32]. However, despite the very long integration times, spectroscopy was limited only to a few brightest objects and to low spectral resolution, hence making it impossible to derive critical information like the dynamical masses through the velocity dispersion of the absorption lines. The distant ETGs spectroscopically identified to date at $1.5 < z < 2.5$ are very red ($R - K > 5$–6), compact ($r_e \approx 0.1$–0.2 arcsec), dominated by passively evolving old stars with ages of 1–4 Gyr, and have stellar masses typically $> 10^{11}$ $M_\odot$, implying a star formation history characterized by strong (> 100 $M_\odot$/yr) and short-lived (0.1–0.3 Gyr) starbursts occurring at $z > 2$–3.

The existence of these old, massive, passive ETGs $z > 1.5$ was unexpected in galaxy formation models available in 2004–2005 and, to date, no new predictions have been published and compared with the available observational data of high-z ETGs. The existence of these galaxies opened the key question on how it was possible to assemble such systems when the Universe was still relatively young. It is generally thought that negative feedback from AGN might play an important role by "quenching" the star formation in ETG precursors (e.g. [25]).

2 Pushing VLT to the Limits: The GMASS Project

The VLT was intensively used in the context of two ESO Large Programmes in order to place constraints on ETG evolution at $z > 1$ (K20 project, [7], and the GMASS project, [21]). In this paper we focus on the latter. GMASS ("*Galaxy Mass Assembly ultra-deep Spectroscopic Survey*"[1]) is a project based on an ESO VLT Large Program (PI A. Cimatti).

The GMASS main scientific driver is to investigate the physical and evolutionary processes of galaxy mass assembly in the redshift range of $1.5 < z < 3$, i.e. in the epoch when the crucial processes of massive galaxy formation took place. Photometric redshifts are not sufficient to fully address the above questions because they provide limited clues on the physical and evolutionary status of the observed galaxies. Spectroscopy is therefore essential to derive reliable spectroscopic redshifts, to perform detailed spectral and photometric SED fitting (with known spectroscopic redshift), and to characterize the nature and diversity of galaxies at $1.5 < z < 3$.

The GMASS sample was selected at 4.5 μm using the GOODS-South[2] public image taken at that wavelength with the *Spitzer Space Telescope* equipped with IRAC (Dickinson et al., in preparation), and extracting from a region of 6.8×6.8 arcmin^2 all the sources with $m_{4.5} < 23.0$ (AB). This flux-limited sample was then used to

[1] http://www.arcetri.astro.it/~cimatti/gmass/gmass.html.

[2] http://www.stsci.edu/science/goods.

extract a sub-sample of target galaxies to be observed spectroscopically. To reach the GMASS scientific aims, spectroscopy was very deep in order to derive secure spectroscopic redshifts for the faintest galaxies and to obtain high-quality spectra for the brighter galaxies in order to allow detailed spectral studies. The GMASS optical multi-slit spectroscopy was done with the ESO VLT + FORS2 (MXU mode) and focused on galaxies pre-selected with a cut in photometric redshift of $z_{phot} > 1.4$ in order to concentrate the study on galaxies in the critical range of $1.5 < z < 3$. In order to make the spectroscopy feasible, two cuts in the optical magnitudes were adopted: $B < 26.5$ or $I < 26.5$ for spectroscopy done in the blue or in the red respectively. The integration times were very long (up to 32 hours per spectroscopic mask), and the spectroscopy was optimized by obtaining spectra in the blue (4000–6000 Å, grism 300V) or in the red (6000–10000 Å, grism 300I) depending on the colors and photometric SEDs of the targets. For both grisms, the slit width was always 1 arcsec and the spectral resolution $\lambda/\Delta\lambda \approx 600$. Despite the faintness of the targets, GMASS spectroscopy provided an overall spectroscopic redshift success rate of about 85% for the targeted galaxies. The power and the novelty of the GMASS sample is the selection at 4.5 μm, which is crucial for two main reasons: (1) the peak of the stellar SEDs ($\lambda_{rest} = 1.6$ μm) is redshifted in the 4.5 μm band for $z > 1.5$, (2) it is sensitive to the rest-frame near-IR emission, i.e. to stellar mass, up to $z \approx 3$. For $m_{4.5} < 23.0$ and a Chabrier IMF, the limiting stellar mass is $\log(\mathcal{M}/M_\odot) \approx 9.8$, 10.1, and 10.5 for $z \approx 1.4$, $z \approx 2$, and $z \approx 3$ respectively, hence allowing to properly investigate the galaxy mass assembly evolution within a wide range of masses.

3 High-z Passive Galaxies

The GMASS spectroscopic sample was mined to search for and study ETGs at $z > 1.4$. Thanks to the combination of the deep spectroscopy, HST + ACS imaging and multi-band photometric SEDs from 0.4 μm to 8 μm, it was possible to study a subsample of 13 ETGs at $1.4 < z < 2$ [10]. However, despite the ultradeep integration times of 32 hours, the faintness of these objects prevented detailed spectral studies of individual galaxies (Fig. 1). Thus, the detailed spectral analysis was done by co-adding the 13 individual spectra to obtain a stacked spectrum with an equivalent integration time of 480 hours (Fig. 2).

The main results can be summarized as follows (see [10] for more details). The GMASS ETGs have spectra and photometric SEDs dominated by old stars and very weak or absent star formation. The comparison of the stacked rest-frame UV spectrum with synthetic stellar population model spectra indicates a stellar age of ≈ 0.7–2.7 Gyr for a metallicity range of 0.2–1.5 $Z_\odot$. Extending the model fitting at longer wavelengths using near-infrared and IRAC photometry helps to reduce the age–metallicity degeneracy and indicates ages of ≈ 1–1.6 Gyr, $Z = Z_\odot$, e-folding timescales $\tau \sim 0.1$–0.3 Gyr, where $\mathrm{SFR}(t) \propto \exp(-t/\tau)$, $A_V \approx 0$ and stellar masses in the range of 10^{10-11} $M_\odot$. The specific star formation rates are consequently very low ($\leq 10^{-2}$ Gyr^{-1}).

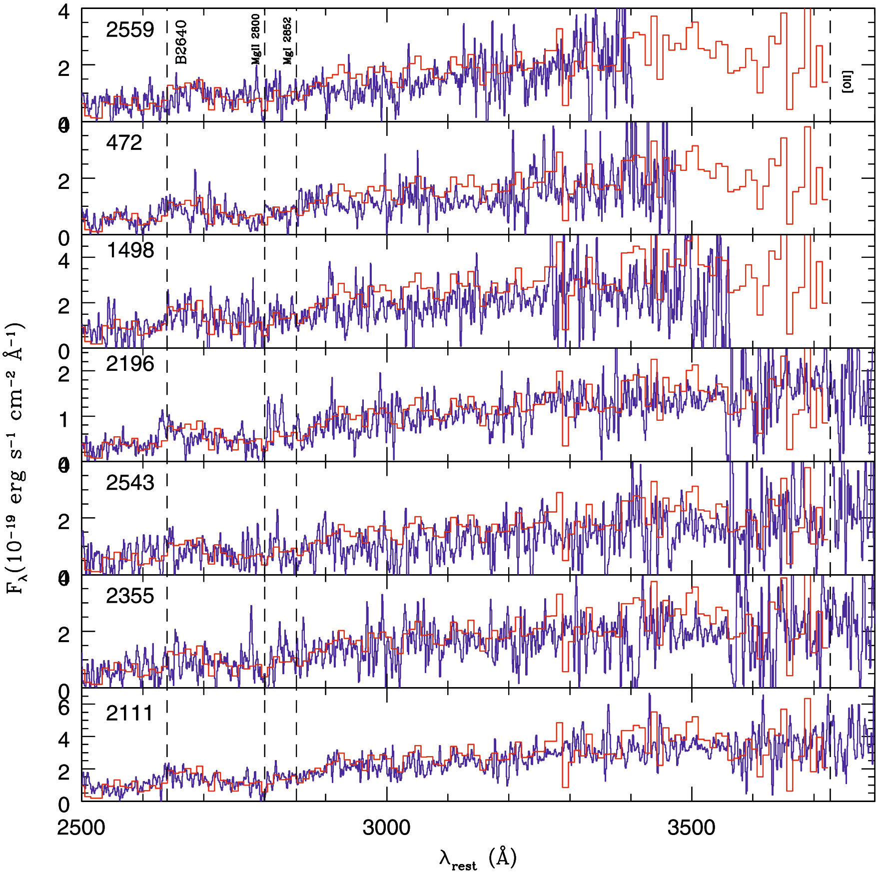

Fig. 1 Individual spectra of ETGs at $z > 1.5$ obtained with the VLT + FORS2 + grism 300I taken in the context of the GMASS project (see [10]). The typical magnitudes are $I \approx 24$–25 (AB) and each spectrum was obtained with an integration time of 32 hours. The histogram line is the spectrum of the old galaxy LBDS 53w091 ($z = 1.55$; [16, 34]) used as a comparison. A colour version of this figure is available at dx.doi.org/10.1007/978-1-4020-9190-2_2

The HST + ACS morphological and surface brightness profile analysis indicate that the majority of the spectroscopically-selected passive galaxies have spheroidal morphologies consistent with being analogous to present-day ETGs. However, their sizes are smaller by a factor of ≈ 2–3 than at $z \approx 0$, and imply that the stellar mass surface and volume internal densities are up to ≈ 10 and ≈ 30 times larger respectively [10, 22, 36, 38]. Submillimeter–selected galaxies are the only systems at $z > 2$ with sizes and mass surface densities similar to those of the passive galaxies at $z \approx 1$–2 [35]. This suggests that an evolutionary link is present between these two galaxy populations. It is currently unclear how these superdense high-z ETGs can evolve from $z \approx 1.5$–2 to $z \approx 0$ and move to the present-day size–mass relation. The possible scenarios proposed so far include a size and mass growth evolution

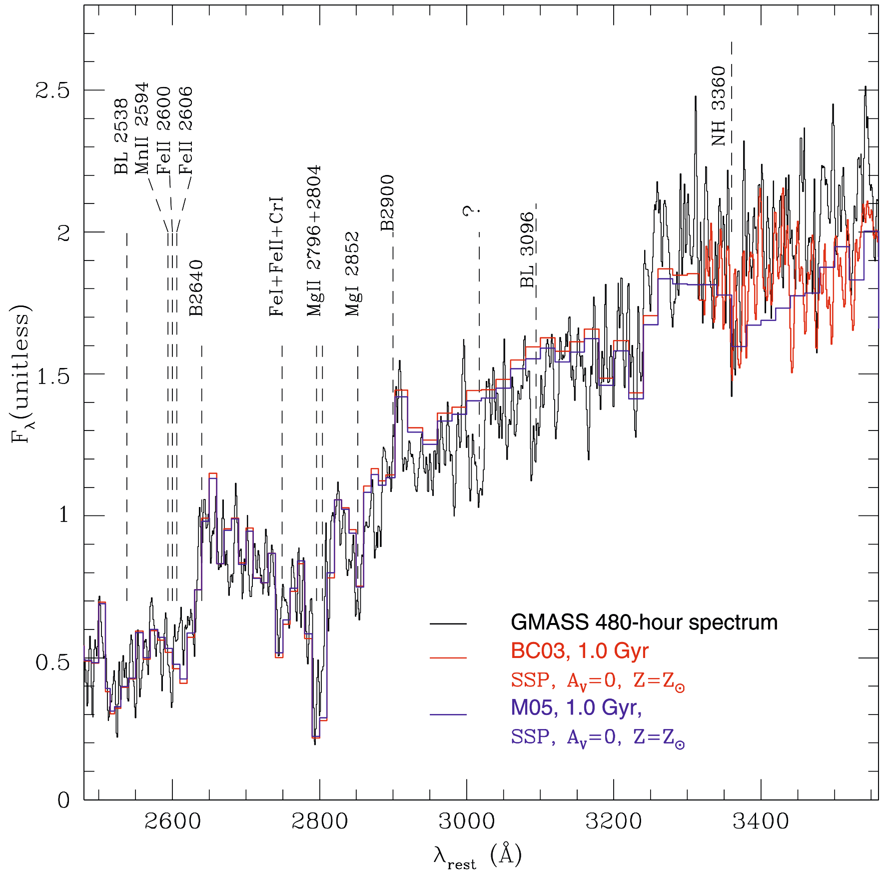

Fig. 2 The co-added spectrum of 13 ETGs at $1.4 < z < 2$ obtained with the GMASS project compared with two synthetic spectra (histogram lines) [4, 23] which provide a good fit of the rest-frame UV spectrum for solar metallicity and age of 1 Gyr (see [10]). The question mark indicates an unidentified absorption feature at ~3018 Å. The co-added spectrum has an equivalent integration time of 480 hours(!) and is publicly available at http://www.arcetri.astro.it/~cimatti/gmass/gmass.html. A colour version of this figure is available at dx.doi.org/10.1007/978-1-4020-9190-2_2

with mechanisms like major dry merging and/or envelope smooth accretion more or less rapidly depending on their mass and environment [1, 2, 11, 15, 18, 19, 26, 27].

4 Open Questions and VLT/E-ELT Requirements

Larger samples of spectroscopically-identified ETGs in the range of $1 < z < 3$ are needed to place stringent constraints on their physical, evolutionary, structural properties and to properly use them as cosmological probes. The key questions still open include the number density evolution, the stellar population content, the star formation and metallicity history, the evolution of scaling relations, the evolution of internal mass density, the environmental effects.

Although this is very challenging from the observational point of view, 8m-class telescopes could still play a role before the advent of JWST and Extremely Large Telescopes (ELTs) if equipped with appropriate instrumentation. For instance, a multi-slit spectrograph with performances and sensitivity optimized in the zYJ spectral region (possibly extended to the H-band) would provide competitive results. For $1 < z < 2$, the key spectral features (e.g. the D4000 break and CaII H&K absorption lines) are redshifted in the zYJ region. A spectral resolution $R \geq 1000$ would be needed for adequate OH sky lines removal and measurement of absorption line velocity dispersions. The surface density of high-z ETGs is in the range of 0.1–0.5 galaxies arcmin^{-2}, and a field of view of $\approx 10 \times 10$ arcmin^{-2} would provide high multiplexing. Due to the small angular sizes of these galaxies (0.1–0.2 arcsec), this instrument would benefit enormously from a ground-layer adaptive optic (GLAO) system providing an "improved seeing" with FWHM $\approx$ 0.1–0.3 arcsec across the field of view. This would allow to narrow the slits and strongly reduce the sky background while still keeping most of the target fluxes within the slits. With such an instrument, the VLT would be capable to obtain competitive results on the brightest envelope of the ETG population at $1 < z < 3$. Moreover, if combined with more traditional optical spectroscopy (0.5–0.8 μm) like the one of GMASS discussed in this paper, the results would place even stronger constraints on the stellar population content and star formation history thanks to the coverage of both the rest-frame UV and optical regions.

A similar instrument on the E-ELT, possibly extended to K-band in order to properly identify spectroscopically and study ETG candidates at higher redshifts (e.g. $z > 4$; [31]) would be essential, and appropriate also for many other studies of high-z galaxies. The ETG science case will also benefit from the synergy with JWST, which will provide rest-frame optical imaging of galaxies with superb spatial resolution over the widest redshift range, as well as low resolution integrated spectroscopy extended in the spectral regions unaccessible from the ground > 2.5 μm.

Finally, we note that the current plans for E-ELT instrumentation do not include an optical multi-object spectrograph. This would preclude the possibility to perform spectroscopy in the rest-frame UV for high-z galaxies, hence making a 42 m telescope "blind" to a wide range of physical processes and diagnostics observable in the UV.

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