The Rest-Frame UV Spectrum of Elliptical Galaxies at High Redshift

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Summary. Beyond redshift \( \sim 1.4 \) the only spectral feature that allows one to get the redshift of passively evolving galaxies (PEG) with optical spectrographs is a characteristic structure due to a set of iron and magnesium lines at \( \lambda \simeq 2600 - 2850 \) Å in the rest frame. The same feature permits also to estimate the time elapsed since the cessation of star formation. Current efforts at observing high redshift PEGs at the VLT and SUBARU telescopes are briefly reviewed.

1 Introduction

In the local universe more than half of the stellar mass resides in passively evolving galaxies (PEG), and above \( \sim 10^{11} M_\odot \) PEGs outnumber starforming galaxies by a factor of 10 or more (e.g. Baldry et al. 2004). As most PEGs are morphologically classified as ellipticals, and most ellipticals are PEGs (e.g., Renzini 2006, Scarlata et al. 2007) sometimes PEGs and ellipticals, or early type galaxies (ETG), are used as synonyms, though there is no perfect overlap, neither at low nor high redshift (e.g. Scarlata et al. 2007). This makes PEGs an especially important class of cosmic objects, and understanding their formation and evolution is central to the broader issue of galaxy formation in general.

Only in recent years it has become possible to observationally map the evolution of the PEG population all the way to fairly high redshifts \( (z \gtrsim 1) \), as a result of combining space and ground observations taken at the most powerful facilities. The ultimate aim of these efforts is that of tracing the evolution with redshift of the number density and mass function of PEGs, all the way to their disappearance, i.e. to the epoch when their precursors were still actively star forming, or were not assembled yet. Thus, to this end three main issues have to be attacked, namely:

- Identify suitable PEG candidates at high redshift,
- Measure their redshift, and
- Estimate age, metallicity and mass of their stellar populations.
In this paper I will briefly report the main results from projects such as the K20 (Cimatti et al. 2002; Mignoli et al. 2005), GMASS (Cimatti et al., in preparation; Kurk et al., in preparation), and a joint ESO/SUBARU project (Kong et al. 2006; Daddi et al., in preparation). Multiobject spectroscopy in the rest-frame ultraviolet has been so far the main tool that has allowed us to precisely locate high-$z$ PEGs in space (and time). Quite similar results are being obtained by the GDDS team, and those are reported by Pat McCarthy at this meeting.

2 PEGs beyond $z \sim 1.4$

The spectroscopic identification of PEGs is relatively easy up to redshift $\sim 1$. As shown in Figure 1, the CaII H&K lines together with the 4000 Å break are the strongest features, and are very effective for measuring accurate redshifts. Large samples of PEGs have then been culled up to this redshift (e.g. Zucca et al. 2005; Faber et al. 2007; Scarlata et al. 2007). However, at higher redshifts these features first become contaminated by atmospheric OH emission, and

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**Figure 1.** A set of co-added spectra from the K20 survey (Mignoli et al. 2005). The top spectrum refers to actively star-forming galaxies, the bottom one to purely passive galaxies, and the middle spectrum refers to mostly passive galaxies with just a sprinkle of star formation.
then move beyond the sensitivity limit of CCD detectors. Hence, other features need to be used to measure redshifts with optical spectrographs.

An inspection of the PEG spectrum in Figure 1 shows that to the blue of the CaII doublet the strongest features are an isolated FeI line at $\lambda \sim 3580$, and a complex feature extending over the range $\lambda = 2600 - 2850$, due to various Fe, MgI and MgII lines, that we call the Mg-UV feature. It is basically thanks to this feature that all redshifts of PEGs at $z > 1.4$ have so far been measured.

The first such case was for a PEG at $z = 1.55$ selected for being a radiogalaxy (Dunlop et al. 1996; Spinrad et al. 1997). Then almost a decade passed before other PEGs at $z > 1.4$ could be spectroscopically identified (5 such objects by Glazebrook et al. 2004, and 4 objects by Cimatti et al. 2004). The most exciting aspect of these 2004 discoveries was that the 9 PEGs were found over a combined field of only $\sim 52$ arcmin$^2$, while the Dunlop et al. object was selected from a catalog covering virtually the whole sky. The clear implication was that massive PEGs at high redshift ought to be much more numerous that many had suspected.

Figure 2 shows the coadded spectrum of the 4 Cimatti et al. objects, along with a synthetic spectrum of a 1.1 Gyr old simple stellar population (SSP). The excellent match between the observed and the synthetic spectrum implies

![Figure 2. The coadded rest-frame UV spectrum of 4 PEGs from the K20 survey (Cimatti et al. 2004). For comparison the synthetic spectrum of a 1.1 Gyr old stellar population with solar metallicity is also shown.](image-url)
that the bulk of stars in the four galaxies had to form at \( z > 2.5 - 3 \), given that they lie at \( 1.6 < z < 1.9 \). Indeed, the power of the Mg-UV feature is that it allows us to get at once the redshift \( \text{and an age estimate, hence to set a formation redshift. This is illustrated in Figure 3, showing that indeed the feature appears only in populations that have evolved passively since at least } \sim 0.5 \text{ Gyr, while the feature is absent for younger ages or for populations with ongoing star formation. Therefore, this feature being observable up to high redshifts is very useful for age-dating PEGs (see e.g., Maraston et al. 2006).}

**Fig. 3.** The synthetic UV spectrum of a simple stellar population at several ages as indicated (from Daddi et al. 2005). Note that the relative fluxes at the various epochs correspond to the passive fading of the stellar population. The spectrum for the case of a time-constant star formation rate is also shown. (Synthetic models are from the library of Bruzual & Charlot 2003.)

Thanks to the Mg-UV feature soon more high-z PEGs were discovered (McCarthy et al. 2004; Daddi et al. 2005), but still within relatively small fields and capitalizing on spectroscopic surveys not specifically targeting such objects. For a more focused spectroscopic study of high-z PEGs an effective criterion for selecting candidates was clearly required.
3 The $BzK$ Criterion for Selecting High-$z$ PEGs

An efficient photometric criterion for the selection of PEGs at high redshift was proposed by Daddi et al. (2004), based on the expected location of $z > 1.4$ PEGs on the $(z-K)$ vs $(B-z)$ two-color diagram. Moreover, the criterion was validated on existing spectroscopic data (K20, GOODS, etc.). The $BzK$ plot from Kong et al. (2006) is shown in Figure 4. Kong et al. then estimated that the comoving volume density of “passive BzKs” (pBzKs) with $M_* > 10^{11} M_\odot$ and $<z> \simeq 1.7$ is only $\sim 20 \pm 7\%$ of the corresponding space density at $z = 0$. Since the majority of such massive PEGs appears to be already in place at $z \sim 1$, this implies that the epoch between $z \sim 2$ and $z \sim 1$ ($\sim 2.5$ Gyr) must be that during which most of massive PEGs are either finally assembled, and/or any residual star formation in their precursors is shut off.

![Fig. 4. The BzK two-color plot from Kong et al. (2006). Following Daddi et al. (2004), four distinct regions are identified, each dominated by PEGs at $z > 1.4$, or pBzKs (upper right, red symbols), star-forming galaxies at $1.4 < z < 2.5$ or sBzKs (upper left, blue symbols), galaxies at $z < 1.4$ (middle, black symbols), and stars (lower section, green symbols). Purple stars indicate Galactic stellar templates.](image-url)
Besides high-z PEGs, the BzK criterion is also very efficient at selecting actively star-forming galaxies at $1.4 < z < 2.5$ (hence called sBzKs), even if rather heavily reddened. The early zCOSMOS spectroscopic results have demonstrated that indeed the contamination by lower redshift interlopers is extremely small for sBzK-selected targets (Lilly et al. 2007). Thus, a sizable fraction of sBzKs must turn into pBzKs and lower redshift PEGs between $z \sim 2.5$ and $z \sim 1$. How this transformation is taking place, in terms of star-formation quenching, merging, disk instability, and morphological transformation is perhaps the major open issue concerning the evolution of galaxies over the last $\sim 11$ Gyr of cosmic time. Of course, this must include the co-evolution of hosting galaxies and their central supermassive black holes (SMBH), and a first grasp at the AGN activity among sBzK galaxies and the concomitant growth of their stellar mass and SMBH can be found in Daddi et al. (2007).

![Graph](https://example.com/fig5.png)

**Fig. 5.** The coadded rest-frame UV spectrum for 17 pBzKs from the sample of Kong et al. (2006) obtained at the VLT with the VIMOS spectrograph (Daddi et al. in preparation). Also shown is the coadded spectrum of K20 PEGs at $z \sim 0.8$, reproduced from Fig. 1.

4 More Rest-frame UV Spectroscopy of High-z PEGs

While extensive multi-object spectroscopy of star-forming galaxies at $z \gtrsim 1.4$ is relatively easy nowadays (e.g. with VIMOS and FORS2 at the VLT and LRIS at Keck), an extensive spectroscopic survey of high-z PEGs is still lacking.
I like to report here some preliminary result from a couple of pilot projects, aiming primarily at understanding how to better plan for future massive surveys.

Figure 5 shows the coadded spectrum for 17 pBzKs selected from the sample of Kong et al. (2006), and observed with the VIMOS spectrograph at the VLT with an integration time of 2.5h (Daddi et al. in preparation). The spectra were taken with the intermediate resolution ($R \sim 600$) Red Grism, while targeting sBzKs and other galaxies as well, so to fully exploit the multiplex of the instrument. Overplotted to the coadded spectrum of the pBzKs is the template spectrum for the $z \simeq 0.8$ PEGs from the K20 survey (from Mignoli et al. 2005).

Figure 6 shows the coadded spectrum for 10 pBzKs selected from the GMASS sample, and observed with the FORS2 spectrograph at the VLT with an integration time of 30h (sic!) (Cimatti et al. in preparation; Kurk et al. in preparation). The spectra were taken with a low resolution ($R \sim 300$) Red Grism. The same lower redshift PEG spectrum is also overplotted. Note that the coadded spectrum in this figure has the same S/N an individual galaxy would have if integrated for 300 hours.

Individual spectra taken with FORS2 have far better S/N than those taken with VIMOS, given the much longer integration time, and the superior performance of FORS2 for $\lambda \gtrsim 8000$ Å. In practice, we are fairly secure that all 10
FORS2 redshifts are correct, while a few (perhaps 3 or 4, or $\sim 20\%$) among the VIMOS redshifts may not be correct.

5 Conclusions

Optical spectroscopic observations in the rest-frame UV have demonstrated that PEGs exist in sizable number up to at least $z \sim 2$. The surface density of $BzK$-selected PEGs is $\sim 0.2$ arcmin$^{-2}$ down to $K = 20$, substantially lower than the slit-packing capability of multiobject spectrographs such as VIMOS or FORS2. Moreover, the rest-frame UV continuum is quite naturally very faint in PEGs, even in high-redshift ones, given that for being passive these galaxies lack OB stars in sizable number. Actually, the absence of these stars is a requisite for detecting the Mg-UV feature.

Therefore, none of the optical instruments currently at 8-10m telescopes is optimally suited to exploit the Mg-UV feature for mapping the population of high-$z$ PEGs. Very long integration times would be required, coupled with only a marginal exploitation for the specific targets of the instrument multiplex.

An alternative option to optical spectroscopy is to go to the near-IR, following the CaII doublet and the 4000 Å break as they redshift beyond $\sim 1\mu$. However, the secure detection even of the strongest absorption lines such as CaII H&K would need extremely long integration times, which could be afforded only if very many objects could be observed simultaneously. The only near-IR MOS currently in operation is MOIRCS at the SUBARU telescope (Tokoku et al. 2006). Several BzK-selected galaxies from the sample of Kong et al. (2006) were ready to be observed with MOIRCS during a 5-night run in April 2007. Unfortunately the spectrographic channel of MOIRCS had a technical problem when just inserting the first cryogenic mask into the instrument, and only the imaging mode could be used in the following nights. As well know, cryogenics is critical for operations in the $K$ band, but a warm instrument working just in the $J$ band would be perfectly adequate for observing the CaII doublet and the 4000 Å break up to $z \sim 2$ and beyond. A first opportunity in this sense will possibly be offered once more by the SUBARU telescope, using the FMOS multifiber instrument (Kimura et al. 2003). With its operation over the large FoV at the prime focus of SUBARU, FMOS will have a very good match between its multiplex and the surface density of pBzKs, and therefore promises to be perhaps a better option for mapping the population of high-$z$ PEGs before JWST. Thus, spectroscopy in the rest-frame ultraviolet has been instrumental for demonstrating the existence of passively evolving galaxies at high redshifts, as well as for validating an efficient photometric criterion for selecting them. However, it appears that near-IR multiobject spectroscopy targeting classical features in the rest-frame optical such as the CaII doublet and the 4000 Å break may be better suited for a massive survey of these objects.
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