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Probing the end of the reionization epoch with the most distant galaxies

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Abstract. As a results of an ultra-deep spectroscopic campaign with FORS2 at the VLT for the confirmation of $z \simeq 7$ "z–band dropout", we found a sharp decrease in the fraction of $Ly\alpha$ emission in LBGs from z∼6 to z∼7, reversing the increasing trend at lower redshift. Explaining the observed rapid change in the Lyα emission fraction with reionization requires a fast evolution of the neutral fraction of hydrogen in the Universe. Assuming that the Universe is completely ionized at z=6 and adopting the semi-analytical models of Dijkstra et al. (2010), we find that our data require a change of the neutral hydrogen fraction of the order $\Delta\chi_{HI} \sim 0.6$ in a time $\Delta z \sim 1$, provided that the UV continuum escape fraction does not increase dramatically over the same redshift interval.

Key words. Galaxies: high redshift; Observational cosmology

1. Introduction

Cosmic reionization was a major event in the early history of the Universe: it marked a drastic transition phase during which the intergalactic space became transparent to UV photons and it is closely related to the birth of the first galaxies. Determining when and how this occurred, the nature of the sources responsible for this transition and the physical processes involved represents one of the latest frontier in observational cosmology.

On the one side the polarization measurement of the cosmic microwave background (CMB) by WMAP implies reionization at z=10.9±1.4 (Komatsu et al. 2009). Conversely, absorption spectra of high-redshift quasars exhibit an increasingly thick Lyα forest, suggesting that the fraction of neutral hydrogen in the intergalactic medium (IGM) is increasing very rapidly from z∼6 (Fan et al. 2006; Pentericci et al. 2002) suggesting a reionization starting at z∼ 7.5. Over the past few years, high redshift Lyman break galaxies (LBGs) and Lyα emitters (LAEs) have rapidly been gaining popularity as probes of cosmic reionization. In particular, the presence and strength of the Lyα (1216 Å) emission line is a very powerful tool to probe reionization: a bright Lyα emission line should be present in all primeval galaxies, which are expected to be young, star forming and virtually dust-free objects. However Lyα photons are highly sensitive to the presence of even a small amount of neutral hydrogen, hence the abundance of Lyα emission galaxies should decrease as observations probe into the era where there are pockets of neutral gas. Star forming galaxies also have several advantages over other reionization probes: specific

Send offprint requests to: L.Pentericci features like the Lyα line and the continuum break bluewards of it, make their identification unambiguous; they are also much more common than bright quasars which are rare and require all sky surveys (Mortlock et al. 2011). The Lyα forest in the spectrum of high-redshift gamma-ray bursts (GRBs) can be an alternative, but the presence of damped Lyα systems within GRB host galaxies complicates the determination of the IGM ionization state.

2. Searching for z$\sim$ 7 galaxies with the VLT

To address these issues we have selected the first homogeneous sample of candidate z$\sim$ 7 galaxies. From deep near-IR Hawk-I observations covering a total area of 200 arcmin^2 on three independent fields (the GOODS-South field -Giavalisco et al. 2004; the NTT Deep Field, Arnouts et al. 1999; and the BDF-4 field -Lenhert & Bremer 2003), we initially selected z-dropouts using an adequate recasting of the Lyman break technique (Castellano et al. 2010). We then carried out systematic spectroscopic observations with FORS2 of the best 20 z$\sim$ 7 candidates. We used the 600Z holographic grating, that provides the highest sensitivity in the range 8000 – 10000Å with a spectral resolution $R \simeq 1390$. Objects were observed for 15-16 hours with median seeing around 0.8$''$. The data were reduced and calibrated following standard procedures that were developed for the GOODS-south spectroscopic campaign (e.g. Vanzella et al. 2009).

In Figure 1 we present the main results of our observations: overall we confirmed the redshift of 5 galaxies at $z \sim 7$, from the presence of the Lyα line (Fontana et al. 2010; Vanzella et al. 2011; Pentericci et al. 2011). One of the 20 observed galaxies is a lower redshift interloper, while the rest of the targets remain undetected. This detection rate is much lower than what expected. As shown by Stark et al. (2011), the fraction of Lyα emission in UV selected galaxies, steadily increases from z$\sim$ 3 to $z \sim 6$: assuming that it keeps increasing to $z \sim 7$, we would expect a much higher number of line emitters, and with more luminous emission lines. Given the relatively small size of our sample we have first assessed the significance of the result: unless we assume that a very high ($\sim$ 40%) fraction of the undetected objects in Lyα are lower redshift interlopers (which is very unlikely, see Section 3) the probability of detecting so few Lyα lines in our sample is extremely low, around 1% . This tells us that the discrepancy between the expected EW distribution and the observed one is very significant, i.e. we have found solid evidence for a decrease in the fraction of Lyα emitting galaxies from z=6 to z=7.

Following our work , similar independent programs by other groups have secured redshifts for a few more galaxies at z$\sim$ 6.8 – 7.2 (Schenker et al. 2012; Ono et al., 2012, Caruana et al. 2012) and have confirmed our findings. At present there are only 10 LBGs with confirmed redshifts at z$\sim$ 6.8 – 7.2, out of more than 45 candidates observed.

3. An increasing neutral IGM?

The drop in the frequency of bright Lyα lines in LBGs could be due to different effects: the most obvious is that the LBG selection might suffer from an increasingly higher interloper fraction, such that a considerable number of our targets are not really at $z \sim 7$. Given the great care in object-selection and the results at z$\sim$ 6, where we find a very low fraction of interlopers (Pentericci et al. 2011, Vanzella et al. 2009) we find this possibility very unlikely. An evolution in the intrinsic properties of the galaxies, such as an increasing dust content at higher redshift, could also provide an explanation for the missing Lyα. However as we go to earlier cosmic epochs we expect to find still younger objects, more metal and dust poor: in this case the production of Lyα photons should be enhanced and we would expect to find an increasing fraction of Lyα emitting galaxies. Alternatively, a very high escape fraction of ionizing photons in high z-galaxies could also reduce the intrinsic Lyα emission (e.g. Dayal et al. 2008) but the evolution of this quantity at high redshift is totally unknown at present (e.g. Boutsia et al. 2011).

We therefore attempt to interpret the apparent fast drop in the LAE fraction among LBGs

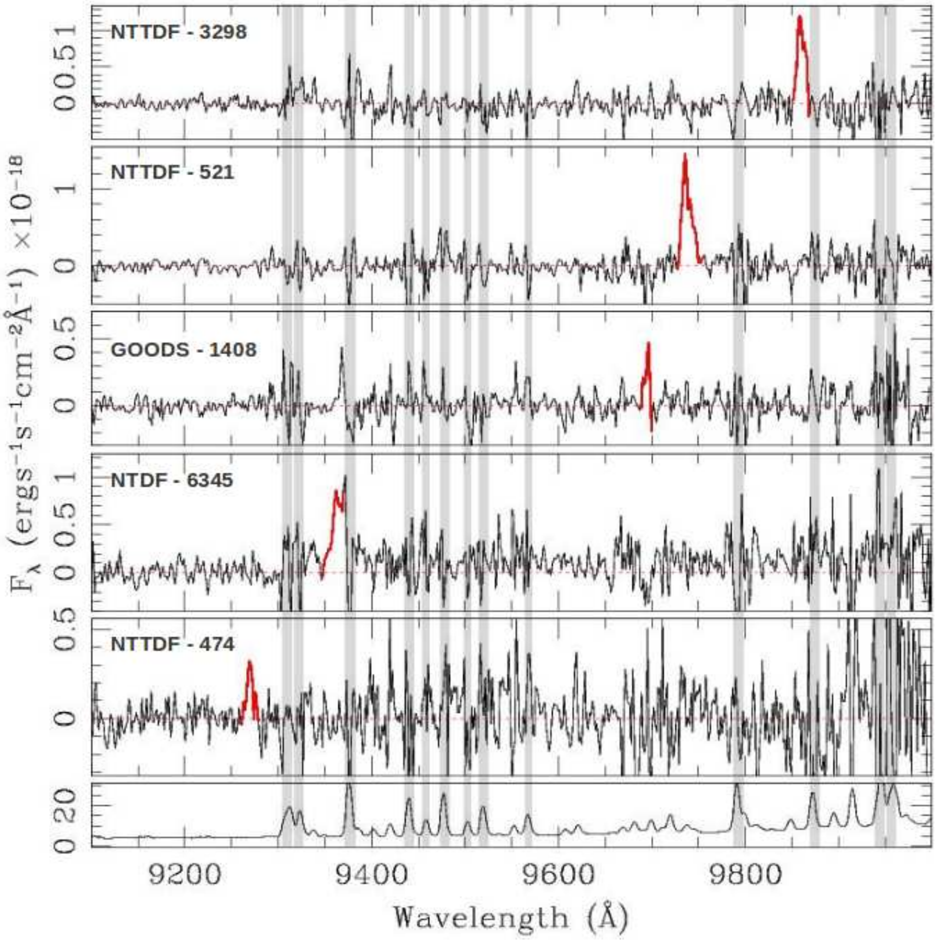

Fig. 1. The extracted 1-D spectra of the 5 confirmed galaxies and of the sky. The bands indicate the positions of the strongest skylines that produce residuals in the reduced spectra.

in terms of an evolving neutral hydrogen fraction at z> 6.5 that could suppress the Lyα emission. To this aim we employ the model developed by Dijkstra et al. (2010), which combines galactic outflow models with large-scale semi-numeric simulations of reionization to quantify the probability distribution function of the fraction of Lyα photons transmitted through the IGM. The observed EW-distribution at z∼ 6 is modeled as an exponential function which provides a good fit to the observed one at lower redshifts, with a scale-length that corresponds to the median value observed by Stark et al. (2010) of 50Å. The IGM at $z \sim 6$ is assumed 100% transparent to Lyα photons emitted by galaxies: the EW probability distribution function at $z = 7$ is different from that at $z = 6$ only because of evolution of the ionization state of the IGM. This exercise is repeated for various fractions of neutral hydrogen (by volume). The results are shown in Figure 2 for two models that differ only for the velocity of the outflowing winds assumed (25-200 km s^{-1}) and have the same column density $N_{HI} = 10^{20} cm^{-2}$. In case of higher velocity the transmitted fraction of Lyα radiation increases; the same is true if the column density is increased. Our observations are consistent with a neutral hydrogen

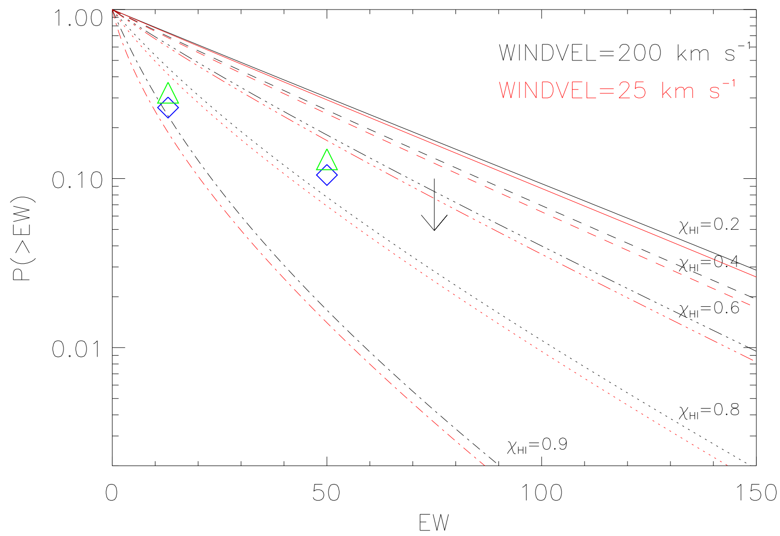

Fig. 2. The expected cumulative distribution of rest frame EWs for z∼ 7 LBGs, assuming that the observed LAE fraction at this redshift is different from z∼ 6 only because of the IGM. The different lines correspond to a Universe that was respectively ∼ 0.2, 0.4, 0.6,0.8 and 0.9 neutral by volume (from top to bottom). The black lines are for the model with $(N_{HI}, v_{wind}) = (10^{20} cm^{-2}, 200 kms^{-1})$, red lines are for $(N_{HI}, v_{wind}) = (10^{20} cm^{-2}, 25 kms^{-1})$. The blue diamonds/green triangles assume that 0%/20% of the undetected galaxies are interlopers. The upper limit for EW=75Å is from Stark et al. (2011).

fraction larger than $\chi_{HI} = 0.60$, even assuming that amongst the undetected objects the fraction of interlopers is as high as 20%. Similar results were recently found by Jensen et al. (2012) using a different model that includes N body simulations, radiative transfer of ionizing radiation, radiative transfer of Lyα through the IGM and Lyα line model.

4. Discussion and future observations

These findings, albeit exciting, are still too preliminary to conclude that we have finally traced the ending of cosmic reionization. There are important uncertainties and limitations that demand a large observational effort to be settled. First of all, the results are presently based on small data-sets, particularly for faintest LBGs, since most previous observations focused on the brighter candidates ($M_{UV} < -20.5$). There are considerable field to field variations: for example the results obtained by Ono et al. (2012) are also consistent with a no evolution of the Lyα distribution from z∼6 to z∼7 at the bright side. The results are also very heterogeneous in terms of wavelength coverage, sample detection and selection: it is therefore hard to combine them and to assess their global statistical significance. Another important uncertainty is related to the Lyα EW distribution at z∼ 6 that is the comparison benchmark to evaluate the evolution over cosmic time.

To provide a definite answer on when and how reionization occurred, we are currently starting a much larger survey over more than 200 LBGs selected from the superb CANDELS data-set (Koekemoer et al. 2011, Grogin et al. 2011) in 3 fields. The VLT spectroscopic observations will allow us to assess the continuous evolution of the Lyα emission over the range $6 < z < 7.3$, and determine when and how the Lyα started to be quenched by the neutral IGM. From a comparison to

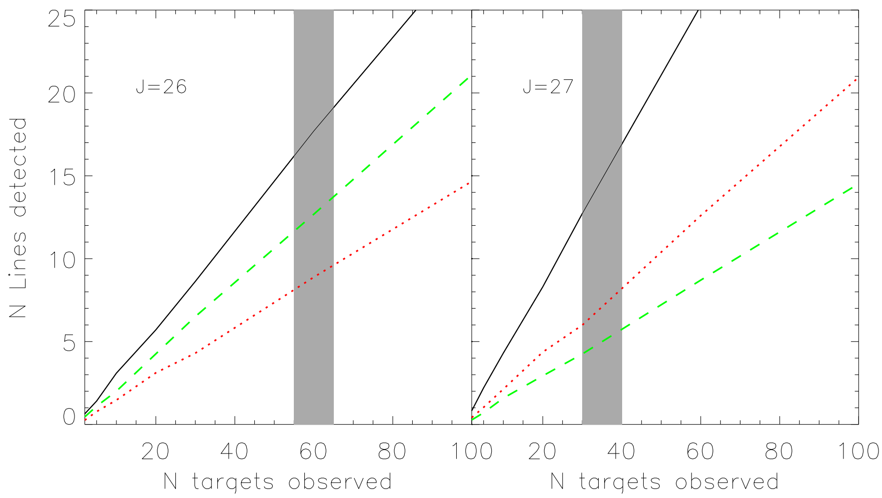

Fig. 3. Predicted detection rates for z∼ 7 galaxies as a function of sample size for various continuum flux. Grey area shows the expected size of our sample (uncertainty is due to the still preliminary analysis of the COSMOS field). The mean number of detections depends on the average opacity of the IGM (the ϵ parameter) and on the patchiness of the reionization process: (1) $\epsilon = 1$ i.e., Lyα distribution as at z∼6 (black solid); (2) patchy reionization with $\epsilon_p = 0.5$ (green dashed), i.e., half the emitters as at z∼ 6; (3) smooth reionization with $\epsilon_s = 0.5$ (red dotted, i.e. half of the luminosity). Observing samples at different fluxes allow us to break the degeneracy between ϵ and the patchiness and hence measure the topology of the reionization process. The predictions are based on the model of Treu et al. (2012)

models we will be able to assess if the transition to fully reionized IGM was smooth or sharp in time. The new observations will also give us a first order view of the complex topology of the reionization process: To this aim we will employ the simple phenomenological model presented by Treu et al. (2012) the proposed samples size will be sufficient to distinguish clearly and for the first time between spatially patchy and smooth Lyα opacity models (see Figure 3 for details).

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