SPECTROSCOPIC OBSERVATION OF Lyα EMITTERS AT $z \sim 7.7$ AND IMPLICATIONS ON RE-IONIZATION

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ABSTRACT

We present spectroscopic follow-up observations on two bright Lyα emitter (LAE) candidates originally found by Krug et al. at a redshift of $z \sim 7.7$ using the Multi-Object Spectrometer for Infra-Red Exploration at Keck. We rule out any line emission at the $> 5\sigma$ level for both objects, putting on solid ground a previous null result for one of the objects. The limits inferred from the non-detections rule out the previous claim of no or even reversed evolution between $5.7 < z < 7.7$ in the Lyα luminosity function (LF) and suggest a drop in the Lyα LF consistent with that seen in Lyman break galaxy (LBG) samples. We model the redshift evolution of the LAE LF using the LBG UV-continuum LF and the observed rest-frame equivalent width distribution. From the comparison of our empirical model with the observed LAE distribution, we estimate lower limits of the neutral hydrogen fraction to be 50%–70% at $z \sim 7.7$. Together with this, we find a strong evolution in the Lyα optical depth characterized by $(1 + z)^2 \pm 0.5$ beyond $z = 6$, indicative of a strong evolution of the intergalactic medium. Finally, we extrapolate the LAE LF to $z \sim 9$ using our model and show that it is unlikely that large area surveys, like UltraVISTA or Euclid, pick up LAEs at this redshift assuming the current depths and area.

Key words: cosmology: observations – dark ages, reionization, first stars – galaxies: formation – galaxies: high-redshift – line: identification

Online-only material: color figures

1. INTRODUCTION

Understanding when and how the universe re-ionized is fundamental to our understanding of how galaxies and large-scale structures form and evolve and is sensitive to global cosmological parameters. In particular, the fraction of neutral hydrogen, $x_H$, in the intergalactic medium (IGM) is closely tied to early galaxy formation because it is related to the gas accretion rate onto galaxies. From current measurements, it is still unclear when re-ionization occurred and what the sources of re-ionizing radiation are.

The best of such current measurements come from cosmic microwave background (CMB) experiments and high-redshift quasar studies, with additional constraints from Lyman break galaxy (LBG) and Lyα-emitting galaxy studies. The Wilkinson Microwave Anisotropy Probe (Larson et al. 2011) and Planck (Tauber et al. 2010) place a $\sim 2\sigma \sim 3\sigma$ constraint on when re-ionization occurred, based on the optical depth to the CMB due to Thompson scattering of electrons. These data are usually fit by a quick re-ionization at $z \sim 10.5$ but are also fully consistent with a more gradual re-ionization with a tail ending at $z \sim 6–7$ (Komatsu et al. 2011; Planck Collaboration et al. 2013). Direct measurements of the optical depth from quasars indicate that the universe is neutral up to $z \sim 7.1$, based on the highest redshift quasars known today (Fan et al. 2006; McLure et al. 2011). Furthermore, ultraviolet (UV)-continuum measurements of LBGs between $z \sim 7–10$ (Bouwens et al. 2011; Bradley et al. 2012; Schenker et al. 2013; McLure et al. 2013) suggest that galaxies have a difficult time re-ionizing the universe until later times, unless the luminosity function (LF) is unusually steep at the faint end or the continuum escape fraction is high (Robertson et al. 2013).

The fraction of strong Lyα emitters (LAEs) within LBG samples should give us a more direct, complementary, and unique measurement of $x_H$, and, therefore, how quickly and when the universe is re-ionizing. Fundamentally, Lyα photons are scattered in areas where the IGM contains more neutral hydrogen, so the escape fraction of Lyα photons is proportional to the volume of re-ionized hydrogen around the young galaxies. Hence, the fraction of galaxies with strong Lyα emission is related to the neutral fraction of the IGM (Haiman & Spaans 1999; Malhotra & Rhoads 2004, 2006; Dijkstra et al. 2007; Dijkstra & Wyithe 2010). However, it is important to note that this probe is also sensitive to the evolution of the interstellar medium (ISM) inside galaxies (like dust; see Bouwens et al. 2012; Finkelstein et al. 2012; Mallery et al. 2012), so one must understand the effects of galaxy evolution to probe the IGM.

The Lyα emission of LBG galaxies (selected using broad bands) is indicative of re-ionization ending at $z \sim 6–7$ and a neutral hydrogen fraction of $\sim 50\%$ at $z \sim 7$ (Fontana et al. 2010; Stark et al. 2010; Pentericci et al. 2011; Ono et al. 2012; Schenker et al. 2012; Caruana et al. 2013). In particular, the fraction of strong LAEs in LBG samples is found to rapidly drop beyond $z > 6.5$ over a range of $\Delta z \gtrsim 1$, a timescale of only $\sim 200$ Myr (Stark et al. 2011; Curtis-Lake et al. 2012; Schenker et al. 2012). An alternative to LBG selection is the use of narrow-band (NB) filters to directly detect LAEs at specific redshifts (e.g., Malhotra et al. 2001; Hu et al. 2004, and references therein). This method allows one to directly map the Lyα LF as a function of redshift, which can then be compared to the LBG UV-continuum LFs to estimate the neutral IGM fraction. An overall change in the Lyα LFs between $5.7 < z < 6.6$ has been firmly established by large samples of spectroscopically confirmed LAEs (Ouchi et al. 2008, 2010; Hu et al. 2010; Kashikawa et al. 2011; Malhotra & Rhoads 2004). But the source of this change could be either an...
evolution in the IGM or a change in the internal ISM of the galaxies. The evolution of the Ly$\alpha$ LF based on LAEs beyond $z > 7$ is far less clear. Apart from a few spectroscopically confirmed LAEs at $z \sim 7$ (one spectroscopically confirmed out of two at $z = 6.96$ (Ota et al. 2008) and one spectroscopically confirmed out of three at $z = 7.22$ (Shibuya et al. 2012a)), there are no confirmed LAEs at higher redshifts. A total sample of $\sim 15$ candidate LAEs at $z = 7.7$ is known (Hibon et al. 2010; Tilvi et al. 2010; Krug et al. 2012). Tilvi et al. (2010) and Krug et al. (2012) favor a non-evolution of the Ly$\alpha$ LF between $5.7 < z < 7.7$ (see also Hibon et al. 2011), which is in tension with other NB searches for LAEs at $z > 7$ that only place limits on the number counts of LAEs (Sobral et al. 2009; Clément et al. 2012; Ota & Iye 2012; Matthee et al. 2014). The reason for this tension may be low-redshift interlopers and false detections in the LAE samples. At $z < 7$, both of these are estimated to contribute less than 10%–20% (see, e.g., Ouchi et al. 2010); at higher redshifts, these contribution are not known yet, but are probably much higher (see Matthee et al. 2014 and this work). Spectroscopic follow-up observations of high-redshift candidate LAEs are therefore necessary to resolve the tensions between the LAE and LBG results at $z > 7$ and to constrain the process of re-ionization at higher redshifts.

In this work, we present Keck-I Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE) spectroscopic follow-up of two $z \sim 7.7$ LAE candidates (Section 2) originally found by Krug et al. (2012). We then go on to compare these results to existing data at lower redshift (Section 3) and to an empirical model derived from the LAE UV-continuum LF and observed equivalent width (EW) distribution (Sections 4.1 and 4.2). This allows us to place limits on the neutral fraction of the IGM at $z \sim 8$ (Section 4.3) and enables us to predict the LAE LF at $z \sim 8–9$ (Section 5).

2. OBSERVATIONS AND ANALYSIS

2.1. Candidate Selection by Krug et al. (2012)

The two targets of our study are among the brightest LAE candidates at $z \sim 7.7$ (12.1 and 8.6 $\times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, respectively, measured in ultra narrow-band (UNB) filters assuming negligible continuum). These targets were initially selected and published by Krug et al. (2012) and, throughout this work, we refer to these as LAE1 (brightest) and LAE2 (second brightest), respectively. Both LAEs were detected with an UNB filter in the COSMOS field (Scoville et al. 2007) using NEWFIRM (Autry et al. 2003). Details of the data reduction and selection are given in Krug et al. (2012) but we give a brief summary of their results here. The effective surface area of the UNB survey is $\sim 760$ arcmin$^2$. The UNB filter used for these candidates is centered at a wavelength of 1.056 $\mu$m and has a width of 8–9 $\AA$. This is a dark region of the spectra between bright night sky lines and selects objects with Ly$\alpha$ emission at a redshift $z \sim 7.7$. The UNB data were acquired over a course of a year in three different sets of observations (2008 February, 2009 February and March). This means transient objects with periods of $< 1$ yr were rejected (see Krug et al. 2012 and later in this section). The total usable observations add up to $\sim 100$ hr distributed over 32 nights, resulting in a limiting magnitude (defined as the 50% completeness limit) of 22.4 AB in the UNB filter. The area used to select these objects is covered by a second UNB filter centered at 1.063 $\mu$m with the same width as well as deep ground-based broad band data from Subaru in the optical (g, B, V, r, i, z) and from UKIRT and Vista in the NIR (Y, J, H, K).

This allows one to exclude continuum on the blue and red side of the potential Ly$\alpha$ emission line and should have eliminated low-$z$ interlopers. Both of the candidates are not detected in any of the broad band filters as well as the second UNB filter. This results in rest-frame EW lower limits of $\sim 7$ $\AA$ and $\sim 5$ $\AA$ for LAE1 and LAE2, respectively.

2.2. MOSFIRE Observations and Data Reduction

We observed the two LAE candidates ($\alpha = 10^h 00^m 46.94$, $\delta = +02^\circ 08' 48''.84$ and $\alpha = 10^h 00^m 20'.52$, $\delta = +02^\circ 18' 50''.04$) with the MOSFIRE (McLean et al. 2012) spectrograph on the Keck-I Telescope on the nights of 2013 January 15 and 16. Each candidate was observed with a separate mask created using the MOSFIRE Automatic graphical-user-interface-based Mask Application (MAGMA, version 1.1) and aligned using bright Two Micron All Sky Survey (2MASS) stars. The conditions were photometric on both nights, with an average seeing around 1$''$. The observations were carried out in Y-band (9710–11250 $\AA$) using the YJ grating and a 0$''$7 slit width, resulting in a resolution of $R = 3270$. We used 180 s exposures with 16 multiple correlated double samples. The telescope was nodded by $\pm 1''$25 with respect to the mask center position between exposures. The total integration times were $46 \times 180$ s $= 8280$ s $= 2.3$ h for LAE1 and $40 \times 180$ s $= 7200$ s $= 2.0$ h for LAE2.

Before creating the mask, we verified that the 2MASS, COSMOS, and NEWFIRM astrometric systems agreed to within measurable errors ($\sim 0.1$). During the observations, we make sure that the masks were properly aligned by using either alignment stars and/or bright filter targets. In addition, several bright sources with known fluxes and morphologies from the z-COSMOS-bright spectroscopic survey (Lilly et al. 2009) were placed on the mask to verify slit losses (estimated to be 40%–50%). We observed 12 and 4 of these galaxies in the LAE1 and LAE2 masks, respectively. The comparison of the expected spatial position from MAGMA to the final spatial position on the reduced two-dimensional (2D) spectra indicates that the alignment was better than 0$''$2 during the observations.

We used the public MOSFIRE python data reduction pipeline for sky subtraction, wavelength calibration, and co-addition of the single exposures. The pipeline performs an A–B/B–A subtraction and co-adds the single exposures using a sigma-clipped noise weighted mean after shifting them to a common pixel frame and masking bad pixels. The atmospheric OH sky lines are used for wavelength calibration. The final 2D spectra have a spatial resolution of 0$''$18 pixel$^{-1}$ and a spectral resolution of 1.09 Å pixel$^{-1}$. Figure 1 shows the final 2D spectra (degraded to $R \sim 1500$) together with the slit positions on sky. We measured an rms noise of $5 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ (4.4 Å resolution element) in the 10545–10565 Å wavelength region, in good agreement with the estimated noise from the MOSFIRE exposure time calculator, corrected for our estimated slit losses.

Absolute flux was measured using the white dwarf spectrophotometric standard star GD71. The standard star was observed

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5 Magnitudes are given in the AB system and we assume a flat universe with $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

6 http://www2.keck.hawaii.edu/inst/mosfire/magma.html

7 N. Konidaris, https://code.google.com/p/mosfire/

8 ETC version 2.3 by G. C. Rudie, http://www2.keck.hawaii.edu/inst/mosfire/etc.html
The Astrophysical Journal, 788:87 (10pp), 2014 June 10

Faisst et al.

Figure 1. Subaru z\textsuperscript{+}-band images centered on LAE1 (top) and LAE2 (bottom) overlaid with the MOSFIRE slits configuration (left). Observed (center) and simulated 2D spectra (right) are shown as well, and both are binned to obtain $R \sim 1500$. The wavelength range where the emission is expected from the UNB observations is marked with red lines. For the simulation shown here, we assumed a rest-frame FWHM of 1.5 Å for the Ly\textalpha line (represented as truncated Gaussian) and a spatial extent of 1″. This simulation shows the clear detection of the line for both LAEs.

(A color version of this figure is available in the online journal.)

Figure 2. Y-band 1σ sensitivity per 4.4 Å resolution element is shown. The measured sensitivity is consistent with that of the exposure time calculator corrected for slit losses. We should be able to detect the two LAE candidates at several $\sigma$ as shown by the red symbols representing their line fluxes as measured in the UNB filter by Krug et al. (2012).

(A color version of this figure is available in the online journal.)

during the same nights with identical settings and reduced in the same way as the science exposures. We present the sensitivity curve for the MOSFIRE Y-band in Figure 2, together with the line fluxes of the two targets derived from UNB filters. This shows that we would have clearly detected the two LAEs as is further discussed below.

2.3. Tests and Simulations: Establishing Our Detection Limits

Assuming the observed fluxes given in Krug et al. (2012) at 10560 Å and based on our measured noise and our seeing of 1″, we expect to detect the two LAE candidates at several $\sigma$ as shown by the red symbols representing their line fluxes as measured in the UNB filter by Krug et al. (2012).

(A color version of this figure is available in the online journal.)

the S/N calculation and lack of detection, we simulated the expected 2D spectra by adding lines to the reduced 2D spectra. For these simulations, we assumed that the total measured flux was distributed over a truncated Gaussian with a rest-frame FWHM ranging from 0.5–3.0 Å (observed from stacked spectra, it is ~1.5 Å, e.g., Hu et al. 2010). For the spatial extent, we assume a Gaussian with FWHM of 1″ corresponding to our seeing. The following results of our simulation are not sensitive to the actual spatial extent. We find that the total flux of such a line would have to be less than ~2–4 × 10\textsuperscript{-18} erg s\textsuperscript{-1} cm\textsuperscript{-2} to not be visible in our data (for the range in rest-frame line FWHM). Vice versa, to miss LAE1 (LAE2) in our data, we would require a rest-frame FWHM of more than 10 Å (7 Å). Figure 1 shows the simulated spectra rescaled to $R = 1500$, assuming the line fluxes measured by Krug et al. (2012), a line rest-frame FWHM of 1.5 Å, and spatial extent of 1″. This shows a clear expected detection of both Ly\textalpha lines.

2.4. No Detection of Ly\textalpha in LAE1 and LAE2

Our firm non-detection of line emission in the targeted LAEs yields an upper limit in Ly\textalpha line flux of 2–4 × 10\textsuperscript{-18} erg s\textsuperscript{-1} cm\textsuperscript{-2}. We therefore rule these candidates out on a 7 and 5$\sigma$ level, respectively. This puts on solid ground a recent less significant non-detection by Jiang et al. (2013) in 7.5 hr of Large Binocular Telescope observation with the LUCI NIR spectrograph. Given these limits, the sources must either be a transient event with decay times of >1 yr, very short periodic (≪1 yr) with a large change in flux, or artifacts and/or noise spikes in the data. Considering transients, the most likely events with similar rates are super-luminous supernovae (SSNe) or active galactic nuclei (AGNs). Low-redshift SNe are favorable because the rest-frame NIR emission is decaying less rapidly than the optical (Tanaka et al. 2012). These events can account for the magnitude change measured in the UNB filters (Quimby et al. 2007; Gezari et al. 2009; Miller et al. 2009). However, a simple calculation suggests that a $z \sim 0.3$ SSN is visible for
a maximum $\sim 230$ days (observed), including the rise of luminosity before its peak. However, Krug et al. (2012) searched for objects with variability on these timescales and removed them; therefore, we believe these are an unlikely source of contamination, although up to three such events could have happened within 0.2 deg$^2$ during the year of observations, depending on initial mass function (IMF; Tanaka et al. 2012). Furthermore, short period AGNs can be excluded as a source of contamination because of the amplitude of the variability, which exceeds that in known AGNs (Vanden Berk et al. 2004; Wilhite et al. 2008; Shibuya et al. 2012b). We thus conclude that the detections are most likely artifacts and noise. There are several reasons why this could happen. First of all, detections near the edges of an image can be caused by enhanced noise. Also, estimates of the limiting magnitude by using 50% completeness simulations and/or the use of inappropriate aperture sizes with respect to the seeing may lead to false detections. In the case of the Krug et al. (2012) candidates, the authors use 50% completeness simulations to estimate their limiting magnitudes. Also, their candidates seem to lie systematically close ($\sim 3''$) to the chip gaps between the four NEWFIRM arrays. Combined with the findings of Clément et al. (2012) and Jiang et al. (2013), who also find no real detections, this raises significant questions about the reliability of the NB filter technique with NIR detectors for detecting LAEs at $z > 7$. Note that for $z < 7$, where large spectroscopic follow-up studies of LAE candidates are possible, the fraction of low-$z$ interlopers and spurious objects is usually <40%.

Whatever the reason, the non-detection of LAE1 and LAE2 in the MOSFIRE spectra places important limits on the LAE LF and implies strong evolution of it at $z > 6$, as will be discussed in the following section.

### 3. The Evolution of the Ly$\alpha$ LF

**From $z = 3.1$ to $z = 7.7$**

A large number of studies have looked at the Ly$\alpha$ LF at $z < 7$. A summary of the surveys at $z \sim 3$–5 is given in Table 1, and the mean data points adopted for this redshift range are shown in Figure 3 panel (A). It can be seen that the LAE LF changes only slightly in this redshift range. Schechter functions fitted to the data as a function of redshift result in less than 15% change in $L^*$ and $\phi^*$, respectively (Ouchi et al. 2008). Note that in this and the following comparisons of LFs, we account for eventual differences in the cosmologies assumed by the authors. Furthermore, some authors apply a correction to their Ly$\alpha$ luminosities to account for absorption of the Ly$\alpha$ forest. This correction is debated, as it was recently shown that the Ly$\alpha$ line profile is asymmetric at $z \sim 0$, where IGM absorption is negligible. This suggests that Ly$\alpha$ is already redshifted when escaping the galaxy and most probably makes the above correction factor superfluous and result in an overestimation of

Table 1

| Redshift | Phot. Candidates | Spec. Confirmed/Observed | Spectr. Fraction | Limits [AB] | Area$^b$ | References |
|----------|------------------|--------------------------|-----------------|-------------|----------|------------|
| 3.1      | 356              | 41/-                     | 12%             | 25.3 (NB505) | 5 × 0.2  | Ouchi et al. (2008) |
| 3.1      | 160              | -                        | 0%              | 25.4 (NB5000) | 1 × 0.28 | Gronwall et al. (2007) |
| 3.7      | 101              | 26/-                     | 26%             | 24.7 (NB570) | 5 × 0.2  | Ouchi et al. (2008) |
| 4.9      | 87               | -                        | 0%              | 26.0 (NB711) | 1 × 0.17 | Ouchi et al. (2003) |

Notes.

$^a$ Fraction of spectroscopically confirmed galaxies used in the analysis.

$^b$ Given in deg$^2$.

The Astrophysical Journal, 788:87 (10pp), 2014 June 10

FAISS et al.

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galaxy, they get scattered in areas of dense neutral hydrogen in the IGM. The amount of neutral hydrogen around galaxies sets the amount of Lyα emission that can be measured by our telescopes. As soon as galaxies are formed, they start to re-ionize larger and larger bubbles of neutral hydrogen around themselves, and the transparency for Lyα photons is increased. By recording the amount of Lyα emission, i.e., the rest-frame EW (EW$_0$) distribution, as a function of redshift, it is therefore possible to estimate the change in the volume fraction of neutral hydrogen, $\chi_{HI}$, and therefore map the re-ionization process. However, the change in the fraction of Lyα-emitting galaxies also depends on the density of the underlying galaxy population as well as on internal (ISM) properties of the galaxies, like star formation rate and dust content. Studies of the Lyα emission properties of \textit{UV-continuum selected LBGs} suggest that the Lyα emission is rising with redshift in galaxies at $z = 4$–$6$ (Stark et al. 2010; Mallery et al. 2012; Schenker et al. 2013), where the universe is thought to be fully re-ionized. In particular, Zheng et al. (2014) note that the EW distribution in this redshift range ($4 < z < 6$) is skewed to larger rest-frame EW values for higher redshifts. This suggests evolution of the internal properties of galaxies (e.g., dust; Bouwens et al. 2012; Finkelstein et al. 2012; Mallery et al. 2012), enhancing the amount of Lyα emission with increasing redshift (e.g., Treu et al. 2012).

In order to constrain the fraction of neutral hydrogen at $z \sim 8$, we have to separate these effects from the IGM. We therefore
first model the intrinsic (i.e., without IGM absorption) \( \text{Ly} \alpha \) LF (Section 4.1). Later, we will compare this intrinsic LF to the observed LFs at different redshifts (Section 4.2) and, combined with two possible implementations of the re-ionization process, constrain \( N_{\text{H}1} \) (Section 4.3).

### 4.1. A Model of the LAE Galaxy Population

To separate IGM from LAE effects on the \( \text{Ly} \alpha \) LF (see also Dijkstra & Wyithe 2012), we first create an empirical model of the LAE LF based on the UV LF and the \( \text{Ly} \alpha \) rest-frame EW (\( EW_{0} \)) distribution at \( z < 6 \), where the IGM is fully re-ionized. In brief, we assume the \( z = 4-9 \) UV-continuum LFs of LBGs derived by Bouwens et al. (2007, 2011) and Oesch et al. (2013). These LFs can be well explained by assuming that the luminosity and stellar mass of a galaxy is directly related to its dark matter halo assembly and gas infall rate (Tacchella et al. 2013). Especially the LF at \( z > 7 \) are therefore put on more solid ground. We then convolve these UV LFs with two observed \( \text{Ly} \alpha \) EW\( _{0} \) distributions. This is not surprising, as from the comparison of the two EW\( _{0} \) distributions it can be seen that Mallery et al. (2012) is missing high EW\( _{0} \) compared to Stark et al. (2010), which results in a much lower \( \text{Ly} \alpha \) LF estimate. In the following, we will assume the Stark et al. (2010) EW\( _{0} \) distribution as the basis because it samples fainter galaxies, which contribute to the majority of objects in our sample while Mallery et al. (2012) is restricted to UV-continuum redshifts and therefore brighter galaxies. To illustrate the dependence on EW\( _{0} \) further, the dotted, dashed, and dash-dotted lines in Figure 4 show constant input rest-frame EWs with EW\( _{0} = 20, 30, 50 \) Å.

### 4.2. Interpreting the Evolution of LAEs

We find good overall agreement between our “predicted” LAE LF and the observed values up to \( z \sim 7 \). But note in Figure 4, the observed LAE LF moves from the bottom of the predicted range at \( 3 < z < 5 \) to the top at \( z \sim 5.7 \). This indicates that the EW\( _{0} \) distribution appears to be skewing to higher values, as found by Zheng et al. (2014) (compare with the lines at constant EW\( _{0} \) in Figure 4), and is likely caused by decreasing amounts of dust. In contrast, at \( z > 7 \), the LAE LF appears to return to the middle or bottom range of the shaded region predicted by our model. Assuming the (intrinsic) EW distribution does not change, then a change in the IGM is needed to reproduce the observation. This indicates the IGM is becoming more opaque at \( z > 7 \), suggesting that re-ionization finished at \( z \sim 6-7 \).
4.3. Constraint on xHII and Lyα Optical Depth at z ~ 7.7

Turning to a more qualitative analysis, we use our model to constrain the change in the neutral hydrogen fraction in the IGM at z > 6.

For this, we consider two different possibilities of how we think Lyα photons get absorbed in the IGM. The two different approaches lead to different imprints of re-ionization in the Lyα LFs. We consider (1) a “black and white” process where Lyα emission in a galaxy is either absorbed or not (“patchy/absorption model”) and (2) a smooth process where the Lyα emission is attenuated by a certain degree (“smooth/attenuation model”).

The former process will decrease the number of Lyα-emitting galaxies irrespective of their emission strength. It will lead to a “global” shift of the LAE LF. The latter process will lower the Lyα emission in all of the galaxies, preferentially removing high Lyα rest-frame EW. It will lead to a change in normalization and shape of the LAE LF.

For both of these models, we can constrain xHII independently. We estimate xHII for the former by using the simulations by McQuinn et al. (2007), and for the latter, we apply the models by Dijkstra et al. (2011).

We note that, with the current data, it is not possible to disprove one of the other approaches. But we will see that both approaches will lead to consistent results.

4.3.1. A Patchy Model of Re-ionization

In this case, Lyα is blocked by the neutral IGM, which results in a decrease of the Lyα LF for all luminosities. We tune our model LF to fit the observed LAE LFs at z ~ 5.7, 6.6, and 7.7 by adjusting X_{Lyα} (the total fraction of galaxies for which Lyα is not absorbed), which is (at first) independent of magnitude (see Figure 5 panels (A) through (C), dotted curves). We find that X_{Lyα} is almost undistinguishable between 5.7 < z < 6.6 but drops by a factor of four beyond z = 7, as shown in Figure 5, panel (D) by the filled squares. Furthermore, we follow the approach of Schenker et al. (2012) and introduce two different values, X_{Lyα}^{bright} and X_{Lyα}^{faint}, for simulated galaxies with M_{UV} < −20.25 AB and M_{UV} > −20.25 AB in order to compare the fraction of LAEs from our empirical model to real observations at z < 7. This is shown in Figure 5 panels (A) and (B) by the dashed line (we do not apply this split at z ~ 7.7 because of the sparse data). The values for X_{Lyα}^{bright} and X_{Lyα}^{faint} for EW_{0} > 25 Å are shown in panel (D) (filled and open circles, respectively).

In general, we find a good agreement of X_{Lyα}(z) with the values observed in UV-continuum selected LBGs at z < 7. We find a significant drop of a factor of 4 ± 1 in the fraction of LAEs at z ~ 7.7 compared to z = 6. Note that the Curtis-Lake et al. (2012) estimate of X_{Lyα} for bright galaxies is a factor of ~2 higher than the estimates from the other studies. Different selection and sample variance are a very likely cause for this discrepancy. Nonetheless, their results support a strong drop of X_{Lyα} above z = 7.

This change in LF can be converted into a neutral hydrogen fraction (xHII) by using the results from the 186 Mpc radiative transfer simulations by McQuinn et al. (2007) as follows: their Figure 4 shows the relative change of the Lyα LF as a function of neutral hydrogen fraction at z = 6.6 assuming full re-ionization at z = 6. For example, xHII = 0.18, 0.38, 0.53, 0.67, and 0.80 result in a rescaling of the LF with factors of 0.76, 0.50, 0.33, 0.20, and 0.05, respectively. We then assume that this rescaling of the LF is directly proportional to the change in the fraction of LAEs, i.e., X_{Lyα,z=7.7}/X_{Lyα,z~<4} (see Figure 5, panel (D), blue and red squares). Assuming the dust extinction properties at z ~ 7.7 are the same as at z = 6, we conclude that the drop in X_{Lyα} implies a neutral hydrogen fraction of at least xHII = 0.60 ± 0.07 at z ~ 7.7. Assuming the dust content of galaxies above z = 6 is further decreasing and therefore extrapolating X_{Lyα}(z) from the values at 4 < z < 6 (see Stark et al. 2010) implies even higher limits (xHII = 0.71 ± 0.04).
that the small change in $X_{\text{Ly} \alpha}$ between $z \sim 5.7$ and $z \sim 6.6$ is indicative of little neutral hydrogen. This is in line with the results by McQuinn et al. (2007), who suggest that the universe is fully ionized at these redshifts.

Note that we can estimate $x_{\text{HI}}$, without applying our model by directly taking the ratio of the LAE LFs at $z \sim 5.7$ and $\sim 7.7$ and again applying the simulations by (McQuinn et al. 2007).

This approach leads to consistent results.

Having established a lower limit on $x_{\text{HI}}$, we can use the patchy model to further constrain the Ly$\alpha$ optical depth. Assuming the change in $X_{\text{Ly} \alpha}$ above $z = 6$ is due to the IGM, it can be associated with the average change of Ly$\alpha$ optical depth ($e^{-\Delta \tau_{\text{Ly} \alpha}}$) under the assumption that re-ionization is completed at $z \sim 6$ (i.e., $\tau_{\text{ly} \alpha, z=5.7} = 0$ and $\Delta \tau_{\text{Ly} \alpha}(z) = \tau_{\text{Ly} \alpha}(z) - \tau_{\text{Ly} \alpha, z=5.7}$). Note that this approach is identical to Treu et al. (2012), and we can set $X_{\text{Ly} \alpha}(z)/X_{\text{Ly} \alpha, z=5.7} \equiv \epsilon_p(z)$, where $\epsilon_p$ is defined as in Treu et al. (2012) and $\epsilon_{p, z=6} = 1$ by construction. From Figure 5 panel (D), we find $\epsilon_p = 0.8 \pm 0.2$ for $z \sim 6.6$ (blue and green squares) and $\epsilon_p = 0.25 \pm 0.05$ for $z \sim 7$ (blue and red squares), respectively. Our $z \sim 6.6$ ($z \sim 7.7$) value is consistent with the $z \sim 7$ ($z \sim 8$) value of $0.66 \pm 0.16$ ($<0.28$) found by Treu et al. (2012) (Treu et al. 2013) within errors. We then compute the Ly$\alpha$ optical depth by equating $\epsilon_p(z) = (e^{-\Delta \tau_{\text{Ly} \alpha}(z)})$.

The final result of $\Delta \tau_{\text{Ly} \alpha}(z)$ w.r.t. $z \sim 6$ is shown in Figure 6. Our limit at $z \sim 7.7$ is important to constrain $\Delta \tau_{\text{Ly} \alpha}(z)$ as the values at $z \sim 6$ and 7 are almost indistinguishable. The overall change in optical depth as a function of redshift can be expressed by $\Delta \tau_{\text{Ly} \alpha}(z) \propto (1 + z)^{\alpha}$ with $\alpha = 2.2 \pm 0.5$. Note that this exponent is a lower limit because of the upper limit in the LAE LF at $z \sim 7.7$. We find an increase in optical depth of at least 1.3 between $z = 6$ and $z \sim 8$. Our best fit model is fully consistent with the Gunn–Peterson optical depth measurements in quasars (Goto et al. 2011; Fan et al. 2006); however, the functional forms of the estimates lead to different exponents (see Figure 6).

4.3.2. A Smooth Model of Re-ionization

In this case, there is no global scaling of the LF as before; however, a steepening of the LF may occur because the EW$_0$ distribution gets skewed to lower EW$_0$ as the redshift increases beyond $z = 6$ (see also Zheng et al. 2014). We represent the Stark et al. (2010) EW distribution in the same manner as Treu et al. (2012) by using a Gaussian truncated at negative values. In contrast to the case outlined before, we now change the width of the EW$_0$ distribution (similar to the “smooth model” in Treu et al. 2012). As in the case above, we have to take the difference in evolution between $z = 6$ and $z = 7.7$ (assuming the IGM is fully re-ionized at $z = 6$). We therefore start directly with the $z = 6$ EW$_0$ distribution (see Figure 6, panel (A), dotted curve) and tune it to fit the $z = 7.7$ limits by changing its width (dashed-dotted line in Figure 6, panel (C)). From the final EW$_0$ distribution at $z = 7.7$, we compute the cumulative fraction $P(>\text{EW}_0)$, which has now changed w.r.t. $z = 6$ as we have adjusted the width of the EW$_0$ distribution. These fractions can be converted into $x_{\text{HI}}$ by using the models by Dijkstra et al. (2011); using semi-numerical simulations by Mesinger et al. (2011), combining galactic outflow models and large-scale semi-numeric simulations of reionization. From our final EW$_0$ distribution fitting the limits at $z \sim 7.7$, we find $P(>100 \text{ Å}) = 0.02 \pm 0.01$, $P(>75 \text{ Å}) = 0.07 \pm 0.02$, and $P(>50 \text{ Å}) = 0.20 \pm 0.05$, which translates, by adopting Figure 5 in Pentericci et al. (2011), into upper limit neutral hydrogen fractions of $x_{\text{HI}} = 0.7 \pm 0.1, 0.6 \pm 0.1$, and $0.5 \pm 0.2$, respectively. Note that $x_{\text{HI}}$ is more difficult to estimate for smaller EW$_0$ cuts as $P(>\text{EW}_0)$ approaches unity for all $x_{\text{HI}}$ by construction (Pentericci et al. 2011). Taking this into account, the limits we find with our second approach are consistent with the results above.

4.3.3. Summary of Our Findings

In summary, we have looked at two different ways how reionization can be imprinted in the change of Ly$\alpha$ LF. We have considered an absorption model resulting in a global shift of the Ly$\alpha$ LF and an attenuation model resulting in a skewing of the EW$_0$ distribution and therefore, a steepening of the Ly$\alpha$ LF. Note that both approaches can fit the observed LAE LFs within its uncertainty, and we are not able to judge which of the models is right. However, a skewing of the EW distribution is likely, as it seems from the observational data at $z \sim 5.7$ and $z \sim 6.6$ that the evolution of the bright end is stronger than at the faint end of the LAE LF. In either way, we are able to constrain $x_{\text{HI}}$ using both approaches, resulting in lower limits for the neutral hydrogen fraction between $x_{\text{HI}} = 0.53$ and $x_{\text{HI}} = 0.70$ at $z \sim 7.7$.

Finally, we stress that our results are based on the assumption that all changes in $X_{\text{Ly} \alpha}$ and the EW$_0$ distribution are caused by a change in the ionization state of the IGM at $z > 6$. However, an alternative explanation involves an increase of the escape fraction of ionizing photons and would lead to a drop in $X_{\text{Ly} \alpha}$ and thus an overestimation of $x_{\text{HI}}$ (Dijkstra et al. 2014). Without a changing ionization state of the IGM, the escape fraction needed to explain the observations is at odds with other studies (Wyithe et al. 2010; Kuhlen & Faucher-Giguère 2012; Robertson et al. 2013; Dijkstra et al. 2014). However, a mixture of changing $X_{\text{HI}}$ ($\sim 0.2$) and $f_{\text{esc}}$ ($\sim 0.2–0.3$) would be consistent with our results and direct escape fraction measurements.

Figure 6. Change in Ly$\alpha$ optical depth with redshift with respect to $z = 6$, assuming the universe is fully re-ionized by then. Under this assumption, we change in optical depth as a function of redshift can be expressed assuming the universe is fully re-ionized by then. Under this assumption, we could be indicative of a dramatic change in the properties of the IGM. Shown along with our best fit is the exponent from the best fit to the evolution of the Gunn–Peterson optical depth measured on Ly$\alpha$, Ly$\beta$, and Ly$\gamma$ transitions in quasars (Goto et al. 2011; Fan et al. 2006). (A color version of this figure is available in the online journal.)
5. EXPECTED NUMBER DETECTIONS OF LAEs AT $z \sim 8.8$ IN OTHER SURVEYS

Given these results at $z \sim 7.7$, it is important to push to higher redshifts to better constrain the evolution of the LAE LF. Assuming that the LAE LF continues to trace the LBG LF at $z > 8$, we can put upper limits on the number of LAEs that should be found in planned surveys. The final UltraVISTA NB118 survey (McCracken et al. 2012; Milvang-Jensen et al. 2013) is able to search for potential LAE candidates at $z \sim 8.8$ on 0.9 deg$^{-2}$ on sky down to $1.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$. Assuming this as limiting the Ly$\alpha$ line flux and combined with our model from the LBG UV LF (optimistically assuming $X_{\text{ly} \alpha}(z = 8.8) = 1$), it is unlikely that this survey will find LAEs at this redshift (expected counts are 0.6 ± 0.3). Likewise, with the same assumptions, Euclid (Laureijs et al. 2011) is not expected to find LAEs at $z > 8$ with its spectroscopic configuration (1.1 μm–2 μm, 3 $\times$ 10$^{-16}$ erg s$^{-1}$ cm$^{-2}$ on 20,000 deg$^2$). On its proposed deep area (40 deg$^2$), a flux limit of at least 3 $\times$ 10$^{-17}$ erg s$^{-1}$ cm$^{-2}$ must be reached to find one LAE at $z > 8$. Other space-based spectroscopic surveys, like WISPS (Atek et al. 2010) or 3D-HST (Brammer et al. 2012) using the Hubble Space Telescope (HST) grism G141, current flux limits around $5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, and area of 600–800 arcmin$^2$, need to be substantially (roughly five times) deeper to find LAEs at $z \sim 8.8$. Very deep small area blind imaging surveys with instruments on 8–10 m telescopes, such as HAWK-I (7.5/7.5) or MOSFIRE (6.1/6.1), must reach flux limits of $5 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ in NB118 to pick up one LAE at $z \sim 8.8$ on a total of ~10 pointings.

6. CONCLUSIONS

We have presented follow-up observations on two bright LAE candidates at $z \sim 7.7$ using MOSFIRE. We rule out any line emission at a level of several $\sigma$ for both objects. The limits inferred from these non-detections suggest a strong evolution of the LAE LF between $6 < z < 8$, consistent with what is seen in LBG samples. We create an empirical model using the observed LBG UV-continuum LFs and Ly$\alpha$ rest-frame EW distributions to understand the interplay between LAE and UV-continuum selected galaxies. We find that our model and the observed LAE LF follow each other but note a secondary effect, which is due to a change in the EW$_{\text{Ly} \alpha}$ distribution of the galaxies as a function of redshift. From this differential evolution and assuming two different models on Ly$\alpha$ absorption, we find consistent lower limits on the neutral hydrogen fraction at $z \sim 7.7$ of 50%–70%. Furthermore, we find a strong evolution in the Ly$\alpha$ optical depth at $z > 6$, which can be characterized by $(1 + z)^{2.10 \pm 0.3}$. All in all, our results are indicative of a continuation of strong evolution in the IGM beyond $z = 7$.

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Facility: Keck:1 (MOSFIRE)
