RAPID DECLINE OF Lyα EMISSION TOWARD THE REIONIZATION ERA*

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ABSTRACT

The observed deficit of strongly Ly α emitting galaxies at z > 6.5 is attributed to increasing neutral hydrogen in the intergalactic medium (IGM) and/or to the evolving galaxy properties. To investigate this we have performed very deep near-IR spectroscopy of $z \gtrsim 7$ galaxies using MOSFIRE on the Keck-I Telescope. We measure the Ly α fraction at $z \sim 8$ using two methods. First, we derived $N_{Ly\alpha}/N_{tot}$ directly, using extensive simulations to correct for incompleteness. Second, we used a Bayesian formalism (introduced by Treu et al.) that compares the z > 7 galaxy spectra to models of the Ly α equivalent width ($W_{Ly\alpha}$) distribution at $z \sim 6$. We explored two simple evolutionary scenarios: pure *number evolution* where $Ly\alpha$ is blocked in some fraction of galaxies (perhaps due to the IGM being opaque along only some fraction of sightlines) and uniform *dimming evolution* where $Ly\alpha$ is attenuated in all galaxies by a constant factor (perhaps owing to processes from galaxy evolution or a slowly increasing IGM opacity). The Bayesian formalism places stronger constraints compared with the direct method. Combining our data with that in the literature, we find that at $z \sim 8$ the Ly α fraction has dropped by a factor of >3 (84% confidence interval) using both the dimming and number evolution scenarios, compared to the $z \sim 6$ values. Furthermore, we find a tentative positive Bayesian evidence favoring the number evolution scenario over dimming evolution, extending trends observed at $z \lesssim 7$ to higher redshift. A comparison of our results with theoretical models implies the IGM volume averaged neutral hydrogen fraction $\gtrsim 0.3$, suggesting that we are likely witnessing reionization in progress at $z \sim 8$.

Key words: early universe – galaxies: evolution – galaxies: high-redshift – intergalactic medium – methods: statistical

Online-only material: color figures

1. INTRODUCTION

With a growing number of spectroscopically confirmed galaxies at z > 6.5, it is evident that there is a dearth of galaxies with high rest-frame Ly α equivalent widths ($W_{Ly\alpha}$). We illustrate this problem in Figure 1, showing the observed $W_{Ly\alpha}$ for galaxies with high spectroscopic confidence at z > 6.5 (Iye et al. 2006; Ouchi et al. 2010; Rhoads et al. 2012; Finkelstein et al. 2013; Pentericci et al. 2014). The lack of high- $W_{Ly\alpha}$ galaxies is not likely due to selection bias, as these galaxies span a wide range of continuum magnitudes (lower panels in Figure 1), i.e., we are not just limited to some brighter UV continuum galaxies causing the observed decline in $W_{Ly\alpha}$. A similar trend is also observed in the Lya fraction of continuum-selected Lyman-break galaxies (LBGs): while the fraction of $Ly\alpha$ galaxies increases from z = 3 to 6 (Stark et al. 2011), there is a marked decline at z > 7(Fontana et al. 2010; Robertson et al. 2010; Vanzella et al. 2011; Ono et al. 2012; Schenker et al. 2012, 2014; Caruana et al. 2012; Treu et al. 2013; Pentericci et al. 2014; Faisst et al. 2014).

Clearly something is changing in the Ly α emitting population at $z \ge 7$. As Ly α emission is sensitive to the neutral hydrogen fraction in the intergalactic medium (IGM: McQuinn et al. 2007), it is tempting to associate the decline in the Ly α fraction with an increasing neutral hydrogen fraction in the IGM, as inferred from QSO sightlines at these redshifts (Fan et al. 2006), because there is no indication that the galaxy properties contributing to $W_{Lv\alpha}$ are evolving rapidly. For example, at 3 < z < 6 (Ouchi et al. 2008; Stark et al. 2011; Mallery et al. 2012; Zheng et al. 2014), where the IGM is mostly ionized (Fan et al. 2002), there is no observed evolution in the $W_{Lv\alpha}$ distribution, which offers insight into the galaxies' physical processes. Also, there is no evolution in the number density of Ly α emitting galaxies in this redshift range (Kashikawa et al. 2006; Iye et al. 2006; Dawson et al. 2007; Ouchi et al. 2008). Clearly, if it were known that the (intrinsic) $W_{Lv\alpha}$ distribution at 3 < z < 6 continues to higher redshift, then the observed decline in $W_{Ly\alpha}$ at z > 7 must stem from an increasing neutral hydrogen fraction in the IGM. For example, Konno et al. (2014) recently reported a marked decline in the number density of Ly α -emitting population at $z \sim 7.3$ from narrow-band imaging, which is consistent with a declining $W_{Ly\alpha}$.

The declining $W_{Ly\alpha}$ distribution could suggest an increasing neutral hydrogen fraction with redshift. This is consistent with recent theoretical studies (e.g., Forero-Romero et al. 2012) that

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Figure 1. Missing high Ly α equivalent width galaxies. Top panel: redshift evolution of rest frame Ly α equivalent width ($W_{Ly\alpha}$) for galaxies with high spectroscopic confidence (Iye et al. 2006; Ouchi et al. 2010; Schenker et al. 2012; Vanzella et al. 2011; Ono et al. 2012; Rhoads et al. 2012; Finkelstein et al. 2013; Pentericci et al. 2014). There is a missing population of high $W_{Ly\alpha}$ galaxies at $z \gtrsim 7$. This deficit is not due to selection bias or observing galaxies with only brighter continuum magnitudes (lower left panel), as these galaxies span a wide range of M_{UV} magnitudes. The clustering of galaxies at $M_{UV} = -20$ is due to the survey limit. The bottom-right panel shows that the galaxies at z < 6.8 and z > 6.8 span a similar range of M_{UV} magnitudes. The dashed line shows a typical $z \gtrsim 7$ spectroscopic survey limit, assuming a Ly α line flux limit 5×10^{-18} erg s⁻¹ cm⁻² (Treu et al. 2013; Finkelstein et al. 2013); current spectroscopic surveys at z > 7 are sensitive to galaxies with $W_{Ly\alpha}$ greater than this threshold.

the observed decline in the Ly α fraction at $z \sim 7$ requires about ~10%–20% neutral hydrogen when combined with fieldto-field variance (Taylor & Lidz 2014), a possibly evolving escape fraction of ionizing photons (Dijkstra et al. 2014), and/or incidence of Ly α absorption systems (Bolton & Haehnelt 2013). If reionization is in fact extremely rapid, with the neutral fraction evolving from >10% to <0.01% in the \leq 200 Myr from $z \sim 7$ and $z \sim 6$, then one would indeed expect a strong evolution in the number of Ly α galaxies formed in this short redshift range (Jensen et al. 2013).

On the other hand, the evolution in Ly α emission may signify evolution in the physical properties of galaxies at z > 6. And indeed, some recent works at z > 7 show some evolution in the physical properties of galaxies. Galaxies at z > 7 have bluer colors (Bouwens et al. 2010; Labbé et al. 2010; Wilkins et al. 2011; Finkelstein et al. 2012; Tilvi et al. 2013, but see also McLure et al. 2011; Dunlop et al. 2012), likely due to lower dust extinction (e.g., Finkelstein et al. 2012), with lower stellar mass (Finkelstein et al. 2010; Schaerer & de Barros 2010) and smaller sizes (Malhotra et al. 2012; Ono et al. 2013). However, if anything, these results, should support the idea that the decline in the $W_{Ly\alpha}$ and Ly α fraction is caused by the increasing neutral hydrogen fraction—lesser dust and smaller masses would make it easier for Ly α photons to escape, unless it is a result of gas accretion (Kereš et al. 2009) with a high covering fraction (but see also Jones et al. 2013). Indeed, this may be the case as empirical arguments suggest that the gas accretion rate exceeds the star formation rate (SFR) at $z \gg 4$ (Papovich et al. 2011). Therefore, there are plausible reasons to suspect that any evolution in the UV continuum properties of LBGs at $z \gtrsim 7$ might also contribute to the evolution in $W_{Ly\alpha}$ (e.g., Finkelstein et al. 2012; Lorenzoni et al. 2013; Bouwens et al. 2014).

In this paper, we measure the redshift evolution of Ly α emission at z > 7 and study the nature of the evolution of $W_{Ly\alpha}$ using simple empirical models. In addition to using our deep spectroscopic observations (Finkelstein et al. 2013), we also combine our data with observations from the literature (Treu et al. 2013), to increase the sample size in order to mitigate the effects of cosmic (field-to-field) variance (Tilvi et al. 2009) and increase the significance from independent data sets. We measure the evolution of the Ly α fraction (the fraction of galaxies with $W_{Ly\alpha}$ above a certain limit) using both a direct measurement of $N_{Ly\alpha}/N_{tot}$ (Section 3.1), and testing the $z > 7 W_{Ly\alpha}$ distribution against that at $z \sim 6$ using a Bayesian formalism against an empirical model (Section 3.2; Treu et al. 2012, 2013). In Section 4 and Section 5 we discuss our results



Figure 2. MOSFIRE *Y*-band spectra of two galaxies that are representative of our sample. The shaded region shows the photometric probability density p(z) for each galaxy. The left panel shows the object that was spectroscopically confirmed with Ly α line detection at z = 7.51 (Finkelstein et al. 2013), with a narrow p(z). The right panel shows an object with no line detection, and a broad p(z). While deriving the Ly α fraction, we use all available information in the 1D spectra, as well as correcting our analysis for p(z) outside our observed spectroscopic wavelength range. (A color version of this figure is available in the online journal.)

and present a summary of our findings, respectively. Where applicable, we assume cosmological parameters $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_0 = 71$ km s⁻¹ Mpc⁻¹.

2. CANDIDATE SELECTION AND SPECTROSCOPIC OBSERVATIONS

To select $z \gtrsim 7$ candidate galaxies for spectroscopic followup, we used extremely deep WFC3/F160W-selected and pointspread function (PSF)-matched photometric catalog (Finkelstein et al. 2013) created using imaging from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CAN-DELS; Grogin et al. 2011; Koekemoer et al. 2011). All candidates were selected using photometric redshifts derived using the photometric redshift code EAZY (Brammer et al. 2008), which uses redshifted spectral energy distribution templates and compares them with the observed multi-band photometry for a given galaxy. In addition to deriving the best-fit photometric redshift, it provides the photometric redshift probability density p(z) for each object. In the following analyses we make use of full photometric redshift distribution instead of just the bestfit redshifts. Each object in our sample was required to have >70% of the integral of p(z) in the primary peak and >25% at z = 7.5-8.5 for the $z \sim 8$ sample and at z = 6.5-7.5 for the $z \sim 7$ sample, and be detected in the F125W and F160W bands at S/N > 3.5. For further details about the candidate selection and data reduction and calibration, we direct the reader to Finkelstein et al. (2013).

We targeted nine $z \sim 8$ and 34 $z \sim 7$ candidate galaxies using Multi-object Spectrometer For Infra-Red Exploration (MOSFIRE: McLean et al. 2012), a near-IR multi-object spectrograph on the Keck Telescope, from 2013 April 17–18. The $z \sim 8$ selection of objects to be put on MOSFIRE masks was prioritized based on magnitude and the amount of p(z) contained within the redshift range 7 < z < 8.2 that was covered by the MOSFIRE Y band.

In this study, we focus on nine $z \sim 8$ galaxies that have spectroscopic observations. The spectroscopic observing conditions were excellent with median seeing FWHM $\simeq 0$?7. We used the MOSFIRE data reduction pipeline to reduce the raw data and extract two-dimensional (2D) wavelength calibrated spectra. To

flux calibrate the one-dimensional (1D) spectra, we used the standard star measurements taken during the same observing nights. We found that the flux errors in the reduced 1D spectra were overestimated. In order to correct these errors, we used the ratio of the standard deviation of flux and the median value of flux errors for a given spectrum, and scaled the flux errors such that this ratio was close to unity (as was done in Finkelstein et al. 2013). The corrected flux errors are consistent with the MOSFIRE exposure time calculator. The typical exposure time per galaxy is about 5–6 hr, which allowed us to reach deep line flux sensitivity of $\simeq 2 \times 10^{-18}$ erg s⁻¹ cm⁻² (5 σ ; although this limit varies with wavelength and the presence of sky emission features).

Our MOSFIRE observations used the *Y*-band filter covering 0.97–1.12 μ m, sensitive to Ly α emission from galaxies at 7 < z < 8.2. Figure 2 shows the spectra of two galaxies typical to our sample, along with their photometric redshift probability densities, p(z). The galaxy in the left panel of Figure 2 has a narrow p(z) with $\mathcal{P}_z \equiv \int_{z=7.0}^{z=8.2} p(z) dz = 99.8\%$, whereas the galaxy in the right panel has a broad p(z) with $\mathcal{P}_z = 45.7\%$.

3. REDSHIFT EVOLUTION OF Lya FRACTION

3.1. Direct Measure

The most straightforward measure of the Ly α fraction is the ratio of the number of galaxies with Ly α emission to the total number of galaxies observed. Figure 3 shows the redshift evolution of the Ly α fraction with $W_{Ly\alpha} > 25$ Å. Formally, none of the objects in our sample are detected with $W_{Ly\alpha}$ greater than this value, and so our measurements of the fraction are upper limits. The open blue squares show the raw Ly α fraction obtained from our deep MOSFIRE observations— $X = N_{Ly\alpha}/N_{tot} < 0.28$ (84% confidence derived from Poisson statistics for zero of four objects with EW > 25 Å) for the brighter ($M_{UV} < -20.25$ mag) sample and X < 0.23 (84% confidence for zero of five objects) for the fainter sample ($M_{UV} > -20.25$ mag).

These raw fractions must be corrected for the wavelength dependent sensitivity of the observed spectra. To estimate this correction we performed extensive simulations, which are



Figure 3. Redshift evolution of the Ly α fraction with $W_{Ly\alpha} > 25$ Å. The left and right panels show results for brighter ($M_{UV} < -20.25$) and fainter samples ($M_{UV} > -20.25$), respectively. The blue open square indicates the uncorrected limit (for our data only; 84% confidence) on the fraction from the direct method (Section 3.1), whereas the filled square shows the limit including completeness corrections and accounting for the photometric redshift distributions. The filled blue circle shows the Ly α fraction derived using the Bayesian formalism (Section 3.2). Red filled squares, the upward-pointing triangle, and downward-pointing triangles are data from (Stark et al. 2011; Curtis-Lake et al. 2012; Ono et al. 2012), respectively. The filled diamond is the combined data taken from Ono et al. (2012), which is composed of data from (Fontana et al. 2010; Pentericci et al. 2011; Schenker et al. 2012). There is a difference in the Ly α fraction estimated from the direct method and Bayesian method that stems from using our data only and using the combined data (with Treu et al. 2013), respectively. However, the unique advantage of using the Bayesian inference is that the results at $z \sim 8$ are *relative* to the $z \sim 6$ distribution. If the drop in the Ly α fraction is due to an increasing neutral hydrogen fraction in the IGM, this occurs over a short (<300 Myr) period, and we are likely witnessing reionization in progress at z > 7.

similar to those described in Stark et al. (2011). First, we inserted artificial sources at random positions along the dispersion direction in the reduced 2D spectra. We then recovered the sources using the same automated method as for the real data: extracting 1D spectra, fitting a Gaussian profile to significant lines, and then computing the S/N from the fit. Emission features with S/N > 5 are considered recovered. The completeness $C'_i(m, W, z)$ for an object is then

$$C'_i(m_i, W_i, z) = N_{\rm rec}/N_{\rm ins},\tag{1}$$

where N_{ins} and N_{rec} are the number of simulated (inserted) and recovered artificial sources in the 2D spectra at a given apparent magnitude, m_i , with Ly α equivalent width W_i , and redshift z.

We must modify the completeness function to account for p(z), because there is a probability of Ly α falling outside the wavelength range covered by the *Y*-band filter for some objects, and thus

$$C_i(m_i, W_i) = \int_{z=7}^{z=8.2} C'_i(m_i, W_i, z) \ p(z) \ dz.$$
 (2)

The effective completeness for all objects with equivalent width W and absolute magnitude M ($M = m - \mu$, where μ is the distance modulus and m is the observed F125W magnitude) is then

$$C_{\rm eff}(M, W) = \sum_{i=1}^{N} C_i(m_i, W_i) / N,$$
 (3)

where *N* is the total number of galaxies in the given (brighter or fainter) sample. The Ly α fraction corrected for incompleteness is then $X_{\text{corr}} = X/C_{\text{eff}}$.

In Figure 3 filled blue squares show the completeness corrected Ly α fraction. The completeness corrected fraction is

 $X_{\text{corr}} < 0.58$ for the brighter subsample, and <0.74 for the fainter sample. For our sample this is primarily a consequence of the fact that the p(z) is not entirely covered by the MOSFIRE *Y*-band observations. On average $\langle \mathcal{P}_z \rangle = 0.45$, which has the effect of nearly doubling the Ly α fraction. For this reason, in the following sections, we explore an alternative method to measure *X*.

3.2. Bayesian Inference

We use a Bayesian formalism developed by Treu et al. (2012) to measure the evolution of the Ly α equivalent width distribution from $z \sim 6$ to z > 7. This method constrains the Ly α equivalent width distribution based on all available information detections, non-detections, wavelength-dependent line-flux sensitivity, and incomplete wavelength coverage (similar to the Direct method with completeness simulations, Section 3.1). An advantage of this formalism is that the results obtained from different data sets or instruments can be easily combined by simply multiplying the posterior probabilities. In addition, the probability at z > 7 is *relative* to the $z \sim 6$ distribution, so any change in $z \sim 6$ equivalent width distribution will change the z > 7 values, accordingly.

Following Treu et al. (2012), we use the observed $z \sim 6 W_{Ly\alpha}$ (Stark et al. 2011) distribution function, $p_6(W_{Ly\alpha})$, modeled as the combination of a Gaussian and a delta function,

$$p_6(W) = \frac{2A}{\sqrt{2\pi}W_c} \exp\left(-\frac{W^2}{2W_c^2}\right) H(W) + (1-A)\delta(W), \quad (4)$$

where we use the shorthand $W \equiv W_{Ly\alpha}$, $W_c = 47$ Å, and A as the fraction of $Ly\alpha$ emitters, taken as A = 0.38 for $M_{uv} < -20.25$ and A = 0.89 for $M_{UV} > -20.25$. H is the Heaviside step function and $\delta(x)$ is the Delta-function.



Figure 4. Cartoon representation of our two evolutionary models—number evolution vs. dimming evolution used in the Bayesian implementation. In the number evolution scenario, only some fraction of $Ly\alpha$ emitting galaxies are visible, either due to transparent sight lines or other physical processes, whereas in the dimming evolution model, $Ly\alpha$ photons from all galaxies are equally attenuated, say for example, due to homogeneous distribution of neutral hydrogen in the IGM. In reality, the observed distribution is likely to be a combination of both scenarios.

The physics of the evolution of $Ly\alpha$ emission is likely very complex, and could involve physical processes associated with the galaxies that depend on redshift, galaxy mass, inclination angle, and so on, as well as a highly inhomogeneous (patchy) IGM with rapidly evolving opacity (see below). Here, we model the evolution of the probability distribution p(W) at z > 6 under two simple empirical cases, as in Treu et al. (2012). These two models do not involve any reionization physics but merely represent how the observed equivalent width distribution at z > 6 compares with $z \sim 6$ distribution. The first limiting case is a number evolution scenario where only some fraction, ϵ_{ne} , of Ly α galaxies are either completely absorbed or do not emit Ly α at all, while the remaining $1-\epsilon_{ne}$ are unattenuated, $p_{ne}(W) = \epsilon_{ne}P_6(W) + (1 - \epsilon_{ne})\delta(W)$. The second limiting case is a uniform dimming evolution model that could correspond to either evolution in galaxy properties or a slowly (and homogeneously) evolving IGM neutral fraction (see Figure 4). Parametrically, the dimming model assumes that $Ly\alpha$ emission from all galaxies at z > 6 is attenuated by the same factor, ϵ_{de} , such that $p_{de}(W) = p_6(W/\epsilon_{de})/\epsilon_{de}$. Our number evolution and dimming evolution models bracket the range of possible physical effects from reionization and galaxy-evolution physics. For example, Jensen et al. (2014, see their Figure 11) and Mesinger et al. (2014) show that patchy reionization may prefer a scenario more similar to our dimming-evolution model. Regardless, the observed equivalent width distribution of $Ly\alpha$ in galaxies is likely a combination of both scenarios. These two models are identical in parameterization to the *patchy* and smooth models of Treu et al. (2012). However, we avoid using the latter nomenclature in order to avoid confusion with the theoretical models that include the physics of reionization.

While these two models are simplistic, they span the full empirical range of evolution in Ly α emission, which allows us to test if the data provide any evidence for the form of the empirical evolution. Reionization is expected to be a highly patchy process based on theoretical expectations (e.g., Furlanetto et al. 2004; Iliev et al. 2006; Zahn et al. 2007; Mesinger & Furlanetto 2008; Finlator et al. 2009). If the evolution of the Ly α emission is a result of such rapid reionization, then we would expect the data to favor the number evolution model. If, on the other hand, the data favor the dimming evolution model, then some other process (or a combination of processes) may be responsible. Therefore, the two models discussed previously provide a starting point for understanding if there is evidence that the evolution in the Ly α emission from galaxies favors number evolution versus dimming evolution. Furthermore, these models have the advantage that their effects on the Ly α distribution function can be solved analytically, and therefore are straightforward to test against observations. The models can also be easily adapted, as more data at z < 7 and z > 7 become available.

3.2.1. Implementation

We now describe how the aforementioned models can be applied to the observations. For an observed spectrum of a galaxy, the observables are the apparent magnitude *m*, the flux density f_i , and the variance σ_i at each pixel *i* corresponding to each wavelength, λ_i , from the spectroscopic data. Following the methodology in Treu et al. (2012, 2013), each wavelength in the spectrum has some likelihood of containing a Ly α emission line with redshift $z_i = \lambda_i/(1216 \text{ Å}) - 1$, and equivalent width *W*. For an unresolved line, we model the distribution function of the line flux density as a Gaussian given by

$$p(f_i, m | W, z_j) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{1}{2} \left(\frac{f_i - W f_m}{\sigma_i}\right)^2},$$
 (5)

where $f_m \equiv f_0 \ 10^{-0.4m} \ c\lambda_0^{-2}(1+z)^{-1}$, $f_0 = 3.631 \times 10^{-20}$ erg s⁻¹ Hz⁻¹ cm⁻². For a resolved line we replace Wf_m in Equation (5) with the line flux distributed as a Gaussian with $\sigma_{\lambda} = 1$ Å (Equation (5) in Treu et al. 2012). In the region (pixels) where there is no emission line contribution $(W = 0), \ p(f_i, m|W, z_j)$ is simply a normal distribution with mean f_i and variance σ_i^2 . The likelihood of the data set, $\{f\}$, given a particular combination of these parameters is then $p(\{f\}, m|\epsilon, z_j) = \int [\prod_i \ p(f_i, m|\epsilon, z_j)] \times p(W|\epsilon) \ dW$.

By Bayes' theorem, the posterior probability on ϵ is then simply the product

$$p(\epsilon, z_j | \{f\}, m) = \frac{p(\{f\}, m | \epsilon, z_j) \times p(\epsilon) \times p(z_j)}{Z}, \quad (6)$$

where this equation is valid for both $\epsilon = \epsilon_s$ and ϵ_p . We adopt a uniform prior $p(\epsilon)$ between 0 and 1 for both cases, where a value of $\epsilon = 1$ would imply no evolution. The prior on $p(z_j)$ is the photometric redshift probability density for each galaxy. Because $p(\{f\}|\epsilon, z_j, m)$ depends on the S/N ratio of the data, it contains the wavelength-dependent sensitivity function. The normalization is $Z = \prod [p(\{f\}, m|\epsilon) \times p(\epsilon) \times p(z_j)]$. Intuitively, smaller values of Z imply that there is less likelihood that the model describes the data. The ratio of this factor between two models (number evolution versus dimming evolution) can be used as evidence in favor of one model over another (e.g., Kass & Raftery 1995). For the simple models used here, Equation (6) can be solved analytically (Treu et al. 2012).

3.2.2. Results

We applied this Bayesian formalism to the spectra of nine galaxies at $z \sim 8$. In the following we derive the results using these nine spectra, as well as combining this sample with that of Treu et al. (2013). Combining our sample of nine galaxies with Treu et al. (2013), nearly doubles the current spectroscopic sample at $z \sim 8$.

Figure 5 shows the posterior probability densities derived from nine $z \sim 8$ spectra in our sample, combined with the posteriors taken from Treu et al. (2013). The 84% confidence intervals on ϵ are derived by integrating the posterior. For our data alone, we obtain $\epsilon_{ne} < 0.56$ and $\epsilon_{de} < 0.74$ at $z \sim 8$ for the number evolution and dimming evolution models, respectively. If we combine these results with those of Treu et al. (2013), we



Figure 5. Posterior probability density of $X_{z\sim 8}$ and $X_{z\sim 6}$. Blue and orange lines show the probability using the combined sample (This work + Treu et al. 2013), for number evolution and dimming evolution models, respectively. Also labeled are the 84% value for both models. Dashed and dotted lines represent probability density using our data set alone. The data provide positive evidence $(2 \ln(Z_p/Z_s) = 2.2)$ in favor of the number evolution model over the dimming evolution model using the significance scale of Kass & Raftery (1995).

obtain $\epsilon_{ne} < 0.30$ and $\epsilon_{de} < 0.25$, for the number evolution and dimming evolution models, respectively.

The normalization of the posteriors allows us to derive the Bayesian evidence between the two models (e.g., Jeffreys 1961; Kass & Raftery 1995).⁸ For our data alone, we find a tentative positive Bayesian evidence favoring the number evolution model, with $2 \ln(Z_{ne}/Z_{de}) = 2.5$. This evidence drops slightly, but remains positive toward the number evolution model with $2 \ln(Z_{ne}/Z_{de}) = 2.2$ when we combine our data with that from Treu et al. (2013). Therefore the evidence is minimally significant that the evolution in the $W_{Ly\alpha}$ distribution at $z \sim 8$ favors the number evolution model.

Qualitatively, the reason the Bayesian evidence favors the number evolution of the $W_{Lv\alpha}$ distribution is that even the relatively small sample sizes are becoming large enough to discriminate between these simple evolutionary models. For example, under the dimming evolution model, the $W_{Ly\alpha}$ distribution shifts such that there are relatively more objects with low $W_{Lv\alpha}$ and fewer objects with high $Ly\alpha$, while the total number of objects with Ly α emission remains unchanged (assuming one can detect the lower levels of Ly α emission). If the true evolution follows the dimming evolution model, then we would expect more $Ly\alpha$ detections at low $W_{Lv\alpha}$, which is not observed and is therefore less favored by the Bayesian analysis. In contrast, in the number evolution model, some fraction of $Ly\alpha$ sources are blocked, keeping the relative distribution of $Ly\alpha$ unchanged, which is favored by the current data. Clearly a larger sample will be needed to confirm these results and/or increase the evidence against the dimming evolution model.

The posterior distribution of ϵ is broader for our sample compared to that of Treu et al. (2013), because we detect Ly α in one object (Finkelstein et al. 2013) and have three other marginal detections ($\simeq 2\sigma - 3\sigma$). In addition, our MOSFIRE *Y*-band observations did not fully cover the p(z) of all nine galaxies. Thus, there is a finite probability that the Ly α line could lie outside the Y-band, which again broadens the ϵ distribution.

4. DISCUSSION

Based on the previously described ϵ constraints, and fitting functions used for the $z \sim 6$ equivalent width distributions, the Ly α fraction in the number evolution model is $X_{z\sim8} = \epsilon_p X_{z\sim6}$, whereas in the dimming evolution case $X_{z\sim8} =$ $\operatorname{erfc}(W/\sqrt{2}\epsilon_s W_c)/\operatorname{erfc}(W/\sqrt{2}W_c)X_{z\sim6}$ where erfc is the complimentary error function.

For our data set alone, the Ly α fractions $X_{z\sim8} < 0.56 X_{z\sim6}$ and $X_{z\sim8} < 0.79 X_{z\sim6}$ (all 84% confidence limits) for number evolution and dimming evolution models, respectively. For the combined data (with Treu et al. 2013), $X_{z\sim8} < 0.30 X_{z=6}$ and $X_{z\sim8} < 0.05 X_{z=6}$ for number evolution and dimming evolution models, respectively. In Figure 3 we show the constraints from the number evolution model only (as this is the conservative limit) as filled blue circles. For the brighter sample, $X_{z\sim8} < 0.06$ and $X_{z\sim8} < 0.01$, whereas for the fainter sample $X_{z\sim8} < 0.16$ and $X_{z\sim8} < 0.03$, for number evolution and dimming evolution models, respectively. The implication is that at z > 7, the fraction of Ly α emitters is reduced by a factor of >3 (84% confidence interval) compared to the fraction at $z \sim 6$. At the 95% confidence interval, the Ly α decline at z > 7 is >2, implying a strong evolution even at this more conservative limit.

4.1. Effect of Using Different $z \sim 6$ Distributions

Our results show that there is strong evidence for evolution in the Ly α equivalent width distribution. The nature of this evolution, however, depends on the assumed z = 6 equivalent width distribution (Stark et al. 2011). Here we test other possible z = 6 Ly α equivalent width distributions to see how this choice affects our conclusions.

To test this effect, Treu et al. (2012) explored the $z \sim 6$ equivalent width distribution with a tail extending toward larger equivalent width objects, similar to Pentericci et al. (2011), for the fainter sample. They found that this equivalent width distribution did not alter their conclusions. We performed a similar test on our data using $z \sim 6$ equivalent width distribution with a uniform tail extending toward higher– $W_{Ly\alpha}$ (150 Å) objects. Using this equivalent width distribution the Bayesian probabilities changed only slightly, with ϵ_{ne} changing from $\epsilon_{ne} < 0.56$ to $\epsilon_{ne} < 0.58$ and ϵ_{de} increasing from $\epsilon_{de} < 0.74$ to $\epsilon_{de} < 0.75$ for our data.

In addition, we explored two more $z \sim 6$ equivalent width distributions: 1) similar to the log-normal distribution used in Schenker et al. (2014) with an additional tail extending toward negative equivalent widths ($W_{Ly\alpha} < -20$ Å), and 2) an extreme distribution with a negative tail extending to $W_{Ly\alpha} < -50$ Å. We show these distributions in Figure 6 and tabulate the results of these tests in Table 1, using our data alone as the results for these distributions are not available from Treu et al. (2013). Thus, it can be seen that our results do not change significantly if the input $z \sim 6$ distribution includes a significant tail extending to very negative equivalent widths. However, if the $z \sim 6$ Ly α distribution is significantly different, for example the one similar to the dotted line (W150) shown in Figure 6, then the derived constraints would be significantly different. The W150 distribution that contains a large number of galaxies with high $W_{Ly\alpha} > 150$ Å yields $X_{z\sim8} < 0.28X_{z=6}$ for the number evolution model, which is much lower compared to the other input equivalent width distributions. Thus, it is important to have

⁸ Kass & Raftery (1995) define the significance scale in favor of one model over the other using the Bayes factors Z_1 and Z_2 as $S = 2 \ln(Z_1/Z_2)$, with S = 0-2 (not worth more than a bare mention), S = 2-6 (positive), S = 6-10 (strong), S > 10 (very strong).

 Table 1

 Results of Using Different $z \sim 6$ Equivalent Distributions for Our Data Alone

Reference	Distribution Type	Sources Used	$\epsilon(W > 25 \text{ Å})$		Lya Fraction	(W > 25 Å)	Evidence
			$\epsilon_{\rm ne}$	$\epsilon_{ m de}$	Relative to $z \sim 6$ $X_{\rm ne}$	X _{de}	Ratio ^a
delta function $W_{Lv\alpha} > 0 \text{ Å}$	Stark+11, Treu+14						
P11	Same as St11 but with	$z \sim 6$	< 0.58	< 0.75	< 0.58	< 0.80	2.3
	tail extending at $W_{LV\alpha} > 100 \text{ Å}$	Pentericci+11, Treu+12					
Sc14	Log-normal like with	3 < z < 6.5	< 0.59	< 0.80	< 0.59	< 0.86	2.4
	negative tail extending at	as in Schenker et al. 2014					
	$W_{\rm Lya} < -20 {\rm \AA}$						
T14 ^c	Same as in Sc14 but with		< 0.59	< 0.81	< 0.59	< 0.86	2.3
	negative tail extending at						
	$W_{\rm Ly\alpha} < -5 {\rm \AA}$						
W150 ^c	Same as P11 but with		< 0.28	< 0.18	< 0.28	< 0.02	6.1
	large number of sources with						
	$W_{Ly\alpha} > 150 \text{ Å}$						

Notes. These values are for our data only. All limits are 84% confidence interval.

^a Bayesian evidence ratio $2 \ln(Z_{ne}/Z_{de})$ derived from our data set alone; see also footnote 9.

^b The value in parenthesis denotes the Bayesian evidence after combining the posterior for our samples with those of Treu et al. (2013).

^c This work.



Figure 6. Different $z \sim 6$ Ly α equivalent width distributions used to test their effect on our results. Legends indicate the different distributions described in Table 1. The dotted line (W150) is an arbitrary distribution chosen to demonstrate how different the $z \sim 6$ equivalent distribution needs to be in order to significantly change the Ly α fraction evolution from the current value. This distribution yields much lower Ly α fraction with $X_{z\sim8} < 0.28 X_{z=6}$ for the number evolution model.

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

a much larger spectroscopic sample of $z \gtrsim 6$ galaxies in order to construct a robust equivalent width distribution at this redshift.

4.2. Physical Interpretation

There are a few possible reasons that can explain the observed sharp decline in the $W_{Ly\alpha}$. It may be that the samples are biased: we may be preferentially targeting only bright continuum galaxies with lower $W_{Ly\alpha}$. However, this is unlikely because Figure 1 shows that the galaxies with $Ly\alpha$ span a wide range of M_{UV} , and that UV continuum limits of $z \gtrsim 7$ surveys are nearly same as that of z < 7 surveys. It may also be that the z > 7 samples include a larger number of lower-*z* contaminants. We think that this is unlikely because it does not explain the steep decline in the $W_{Ly\alpha}$ values (top panel in Figure 1) in spectroscopically detected galaxies at z > 6.5,

It may be the evolution in the intrinsic galaxy properties that is responsible. Previous work has shown that galaxies at z > 6have lower dust extinction (e.g., Finkelstein et al. 2012), smaller sizes, and lower stellar mass, making it easier for $Ly\alpha$ photons to escape. Robertson et al. (2010) also found evolution in the UV continuum properties of galaxies, and discussed how this may contribute to the decline in the $W_{Ly\alpha}$ in spectroscopic samples. Galaxies at z > 7 may also have higher gas accretion rates relative to their SFRs than lower redshift galaxies (e.g., Papovich et al. 2011; Finkelstein et al. 2012), which could suppress the escape of Ly α photons depending on the gas dynamics (infall velocity versus outflow rates), or if the covering fraction of the infalling gas is large. On the other hand, recent work (e.g., Iwata et al. 2009) implies that the Lyman-continuum photon escape fraction should be *higher* at z > 3 than at lower redshift to account for reionization, but see also Boutsia et al. (2011) where they find a low continuum escape fraction in Lymanbreak selected galaxies at z = 3.3.

While some evolution of the physical properties of z > 7galaxies occurs, it seems that galaxy evolution alone is unable to account for the decline in the Ly α distribution. Rather, the most plausible explanation is that both a changing neutral hydrogen fraction in the IGM and evolution from galaxy properties contribute to the decline in the $W_{Ly\alpha}$ distribution. Based on our results, the fraction of galaxies with strong Ly α equivalent widths has dropped significantly from $z \sim 6.5$ to z > 7. If this suppression in Ly α emission is solely due to the IGM evolution, it can be directly interpreted as an increase in the optical depth, $\Delta \tau_{Ly\alpha}$, from z = 6.5 to z = 7.5, where $\langle \exp(-\Delta \tau_{Ly\alpha}) \rangle = \epsilon$ (for both the number and dimming evolutionary models). Based on our results, in a simplistic case where reionization is uniform, the conservative limit on the optical depth of $\Delta \tau_{Ly\alpha} > 1.2$ (84%) confidence interval) at $z \sim 7.5$. This is similar to the rapid evolution in the opacity of the Gunn & Peterson (1965) trough, where the extrapolated relation from Fan et al. (2006) predicts $\Delta \tau = (1 + z_{7.5})/(1 + z_6)^{4.3} = 2.3.$

The observed rapid decline in the Ly α fraction is consistent with recent theoretical predictions. However, these studies suggest that at $z \sim 7$ we need only a $\sim 10\%$ -20% neutral hydrogen fraction to explain the observed Ly α fraction decline if we account for cosmic variance, evolving escape fraction of ionizing photons and increasing incidence of optically thick absorption systems (Bolton & Haehnelt 2013; Taylor & Lidz 2014; Dijkstra et al. 2014). Mesinger et al. (2014) argue based on their model that, at 68% confidence, the decline in the Ly α fraction at $z \sim 7$ from lower redshift cannot be greater than a factor of two unless galaxy evolution processes also contribute to the decline in Ly α photons. However, at 95% confidence the observed decline in Ly α may stem solely from the evolution of the IGM in their model. At z > 7, however, it is possible that there is in fact a more rapid increase in the neutral hydrogen fraction, which may explain the steep observed decline of $Ly\alpha$ equivalent widths of individual galaxies (see Section 4.3 below). To investigate and minimize these observational uncertainties, we therefore need much larger spectroscopic samples of z > 7galaxies.

In addition to the declining Ly α fraction, our simplistic models show the first tentative evidence toward a number evolution scenario at z > 7, extending recent results seen at $z \lesssim 7$ (Pentericci et al. 2014). Therefore, the data support the idea that some process related to decreasing high $W_{Ly\alpha}$ galaxies is dominant. This is consistent with reionization where regions are opaque, likely due to neutral hydrogen, which blocks a fraction of sightlines while leaving others unaffected. This makes the prediction that if we survey enough area, we should find objects with high $W_{Ly\alpha}$, but they should be rare. Indeed, there is a recent report of a weak detection (~4 σ) of a galaxy at z = 7.6 with $W_{Ly\alpha} = 160$ Å (Schenker et al. 2014), which if confirmed could further support our interpretation.

4.3. Implications for Reionization

Several theoretical studies using semi-analytical and numerical simulations have developed models of IGM evolution and its effect on the observations (e.g., Miralda-Escudé et al. 2000; Ciardi et al. 2006; Gnedin & Fan 2006; Furlanetto & Pritchard 2006; McQuinn et al. 2007; Mesinger & Furlanetto 2008; Choudhury et al. 2009; Crociani et al. 2011; Dijkstra et al. 2011; Alvarez & Abel 2012; Jensen et al. 2013). In this section, to estimate the neutral hydrogen fraction f_{HI} at $z \sim 8$, we use two different models that predict the probability of Ly α equivalent widths given a certain neutral hydrogen fraction in the IGM combined with line-of-sight Ly α absorbers (Bolton & Haehnelt 2013) and models that include an evolving escape fraction of ionizing photons (Dijkstra et al. 2014).

Figure 7 shows the cumulative probability distribution of Ly α equivalent widths comparing our results with the theoretical predictions from Bolton & Haehnelt (2013) and Dijkstra et al. (2014) for the fainter sample. Our results are shown only for the number evolution model. The Cyan-filled region shows model predictions at $z \sim 7$ from Bolton & Haehnelt (2013) for a range of Ly α velocity offsets from 200 to 600 km s⁻¹, photo-ionization rate $\log(\Gamma_{\rm H\,I}/S^{-1}) = -14$, and volume average neutral hydrogen fraction of $f_{\rm H\,I} \sim 0.1$. The yellow-filled region shows the model prediction at $z \sim 8$ (Dijkstra et al. 2014) for $f_{\rm H\,I} \sim 0.3$ and the escape fraction of ionizing photons $\langle f_{esc} \rangle = 0.04[(1 + z)/5]^4$. Compared with these model predictions, our current Ly α emitter fraction is lower by a factor of \sim 2. Thus, we conclude that the neutral hydrogen fraction at $z \sim 8$ is $f_{\rm H_{I}} \gtrsim 0.3$, considering the evolution of the neutral hydrogen fraction, as well as the evolving galaxy properties, such as winds, ionizing escape fraction, and so on. If the decline is solely due to the reionization, the amount of the neutral hydrogen fraction at $z \sim 8$ will be much higher, because



Figure 7. Cumulative Ly α probability distribution for the faint sample ($M_{\rm UV} > -20.25$ mag) and comparison of model predictions (Bolton & Haehnelt 2013; Dijkstra et al. 2014) to estimate the neutral hydrogen fraction in the IGM at $z \sim 8$. The dashed line shows the reference $z \sim 6$ Ly α EW distribution used in the models, which is equivalent to a neutral hydrogen fraction $f_{\rm H1} \sim 0$, whereas open squares represent $z \sim 6$ observations from Stark et al. (2011), used in our Bayesian models. Cyan-filled regions show model predictions at $z \sim 7$ for a volume averaged $f_{\rm H1} \sim 0.1$ (Bolton et al. 2014). Filled gray squares are the observations from Ono et al. (2012, and references therein). The yellow-filled region shows the model prediction at $z \sim 8$ (Dijkstra et al. 2014) for $f_{\rm H1} \sim 0.3$. Our results, shown in filled blue circles (shown only for the number evolution scenario), are significantly lower compared with the model predictions. This implies that the volume-averaged neutral hydrogen fraction at $z \sim 8$ is at least $f_{\rm H1} \gtrsim 0.3$.

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

the model predictions (Bolton & Haehnelt 2013; Dijkstra et al. 2014) in Figure 7 already include some galaxy evolution. This is consistent with inferences of the neutral hydrogen fraction based on the evolution of the UV and Ly α luminosity functions (Robertson et al. 2013; Konno et al. 2014), and thus, the reionization of the universe is likely in progress at $z \sim 8$.

5. SUMMARY

We investigated the evolution of the Ly α fraction from $z \sim 6$ to $z \sim 8$ using extremely deep spectroscopic observations of nine galaxies, obtained using the MOSFIRE Y-band that covers the redshift range 7 < z < 8.2. We explored two different methods to study the Ly α fraction: a direct method with extensive completeness simulations to account for the incompleteness, and a Bayesian inference method using two simplistic models—number evolution versus dimming evolution.

The Bayesian method yields much stronger constraints than the direct method due to its relative inference—the Ly α fraction at $z \sim 8$ is relative to the $z \sim 6$ values, and any change in $z \sim 6$ values will change the derived $z \sim 8$ values accordingly. Combining our data with that of Treu et al. (2013), we found that the Ly α fraction at $z \sim 8$ has dropped significantly, by a factor of >3 (84% confidence), compared with $z \sim 6$ values. However, it may be that the other factors, such as (rapid) evolution in galaxy properties or field-to-field variations, also affect the Ly α emission distribution.

Our results show a tentative positive evidence toward the number evolution model with a Bayesian evidence ratio of 2 $\ln(Z_{ne}/Z_{de}) = 2.2$ extending earlier $z \sim 7$ results to higher redshift, z > 7. Furthermore, comparing our results with theoretical predictions, we find that the neutral hydrogen fraction f_{HI} at $z \sim 8$ is ≥ 0.3 . To corroborate these results further, and understand how the Ly α width distribution function evolves from z = 6 to z > 7, we need larger samples of galaxies (particularly with high $W_{Ly\alpha}$). Only with that knowledge can we constrain the nature of reionization.

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REFERENCES

- Alvarez, M. A., & Abel, T. 2012, ApJ, 747, 126
- Bolton, J. S., & Haehnelt, M. G. 2013, MNRAS, 429, 1695
- Boutsia, K., Grazian, A., Giallongo, E., et al. 2011, ApJ, 736, 41
- Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2010, ApJL, 708, L69
- Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2014, arXiv:1403.4295
- Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503
- Caruana, J., Bunker, A. J., Wilkins, S. M., et al. 2012, MNRAS, 427, 3055
- Choudhury, T. R., Haehnelt, M. G., & Regan, J. 2009, MNRAS, 394, 960
- Ciardi, B., Scannapieco, E., Stoehr, F., et al. 2006, MNRAS, 366, 689
- Crociani, D., Mesinger, A., Moscardini, L., & Furlanetto, S. 2011, MNRAS, 411, 289
- Curtis-Lake, E., McLure, R. J., Pearce, H. J., et al. 2012, MNRAS, 422, 1425
- Dawson, S., Rhoads, J. E., Malhotra, S., et al. 2007, ApJ, 671, 1227
- Dijkstra, M., Mesinger, A., & Wyithe, J. S. B. 2011, MNRAS, 414, 2139
- Dijkstra, M., Wyithe, S., Haiman, Z., Mesinger, A., & Pentericci, L. 2014, MNRAS, 440, 3309
- Dunlop, J. S., McLure, R. J., Robertson, B. E., et al. 2012, MNRAS, 420, 901
- Faisst, A. L., Capak, P., Carollo, C. M., Scarlata, C., & Scoville, N. 2014, ApJ, 788, 87
- Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
- Fan, X., Narayanan, V. K., Strauss, M. A., et al. 2002, AJ, 123, 1247
- Finkelstein, S. L., Papovich, C., Dickinson, M., et al. 2013, Natur, 502, 524
- Finkelstein, S. L., Papovich, C., Giavalisco, M., et al. 2010, ApJ, 719, 1250
- Finkelstein, S. L., Papovich, C., Salmon, B., et al. 2012, ApJ, 756, 164
- Finlator, K., Özel, F., Davé, R., & Oppenheimer, B. D. 2009, MNRAS, 400, 1049

- Fontana, A., Vanzella, E., Pentericci, L., et al. 2010, ApJL, 725, L205
- Forero-Romero, J. E., Yepes, G., Gottlöber, S., & Prada, F. 2012, MNRAS, 419, 952
- Furlanetto, S. R., Hernquist, L., & Zaldarriaga, M. 2004, MNRAS, 354, 695
- Furlanetto, S. R., & Pritchard, J. R. 2006, MNRAS, 372, 1093
- Gnedin, N. Y., & Fan, X. 2006, ApJ, 648, 1
- Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, ApJS, 197, 35
- Gunn, J. E., & Peterson, B. A. 1965, ApJ, 142, 1633
- Iliev, I. T., Mellema, G., Pen, U.-L., et al. 2006, MNRAS, 369, 1625
- Iwata, I., Inoue, A. K., Matsuda, Y., et al. 2009, ApJ, 692, 1287
- Iye, M., Ota, K., Kashikawa, N., et al. 2006, Natur, 443, 186
- Jeffreys, H. 1961, Theory of Probability (3rd ed.; Oxford: Oxford Univ. Press) Jensen, H., Hayes, M., Iliev, I., et al. 2014, arXiv:1406.1358
- Jensen, H., Laursen, P., Mellema, G., et al. 2013, MNRAS, 428, 1366
- Jones, T. A., Ellis, R. S., Schenker, M. A., & Stark, D. P. 2013, ApJ, 779, 52
- Kashikawa, N., Shimasaku, K., Malkan, M. A., et al. 2006, ApJ, 648, 7
- Kass, E. R., & Raftery, E. A. 1995, JASA, 90, 430
- Kereš, D., Katz, N., Fardal, M., Davé, R., & Weinberg, D. H. 2009, MNRAS, 395, 160
- Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, ApJS, 197, 36
- Konno, A., Ouchi, M., Ono, Y., et al. 2014, arXiv:1404.6066
- Labbé, I., González, V., Bouwens, R. J., et al. 2010, ApJL, 716, L103
- Lorenzoni, S., Bunker, A. J., Wilkins, S. M., et al. 2013, MNRAS, 429, 150
- Malhotra, S., Rhoads, J. E., Finkelstein, S. L., et al. 2012, ApJL, 750, L36
- Mallery, R. P., Mobasher, B., Capak, P., et al. 2012, ApJ, 760, 128
- McLean, I. S., Steidel, C. C., Epps, H. W., et al. 2012, Proc. SPIE, 8446, 84460J
- McLure, R. J., Dunlop, J. S., de Ravel, L., et al. 2011, MNRAS, 418, 2074
- McQuinn, M., Hernquist, L., Zaldarriaga, M., & Dutta, S. 2007, MNRAS, 381, 75
- Mesinger, A., Aykutalp, A., Vanzella, E., et al. 2014, arXiv:1406.6373
- Mesinger, A., & Furlanetto, S. R. 2008, MNRAS, 386, 1990
- Miralda-Escudé, J., Haehnelt, M., & Rees, M. J. 2000, ApJ, 530, 1
- Ono, Y., Ouchi, M., Curtis-Lake, E., et al. 2013, ApJ, 777, 155
- Ono, Y., Ouchi, M., Mobasher, B., et al. 2012, ApJ, 744, 83
- Ouchi, M., Shimasaku, K., Akiyama, M., et al. 2008, ApJS, 176, 301
- Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2010, ApJ, 723, 869
- Papovich, C., Finkelstein, S. L., Ferguson, H. C., Lotz, J. M., & Giavalisco, M. 2011, MNRAS, 412, 1123
- Pentericci, L., Fontana, A., Vanzella, E., et al. 2011, ApJ, 743, 132
- Pentericci, L., Vanzella, E., Fontana, A., et al. 2014, arXiv:1403.5466
- Rhoads, J. E., Hibon, P., Malhotra, S., Cooper, M., & Weiner, B. 2012, ApJL, 752, L28
- Robertson, B. E., Ellis, R. S., Dunlop, J. S., McLure, R. J., & Stark, D. P. 2010, Natur, 468, 49
- Robertson, B. E., Furlanetto, S. R., Schneider, E., et al. 2013, ApJ, 768, 71
- Schaerer, D., & de Barros, S. 2010, A&A, 515, A73
- Schenker, M. A., Ellis, R. S., Konidaris, N. P., & Stark, D. P. 2014, arXiv:1404.4632
- Schenker, M. A., Stark, D. P., Ellis, R. S., et al. 2012, ApJ, 744, 179
- Stark, D. P., Ellis, R. S., & Ouchi, M. 2011, ApJL, 728, L2
- Taylor, J., & Lidz, A. 2014, MNRAS, 437, 2542
- Tilvi, V., Malhotra, S., Rhoads, J. E., et al. 2009, ApJ, 704, 724
- Tilvi, V., Papovich, C., Tran, K.-V. H., et al. 2013, ApJ, 768, 56
- Treu, T., Schmidt, K. B., Trenti, M., Bradley, L. D., & Stiavelli, M. 2013, ApJL, 775, L29
- Treu, T., Trenti, M., Stiavelli, M., Auger, M. W., & Bradley, L. D. 2012, ApJ, 747, 27
- Vanzella, E., Pentericci, L., Fontana, A., et al. 2011, ApJL, 730, L35
- Wilkins, S. M., Bunker, A. J., Stanway, E., Lorenzoni, S., & Caruana, J. 2011, MNRAS, 417, 717
- Zahn, O., Lidz, A., McQuinn, M., et al. 2007, ApJ, 654, 12
- Zheng, Z.-Y., Wang, J.-X., Malhotra, S., et al. 2014, MNRAS, 439, 1101