Beacons into the Cosmic Dark Ages: Boosted Transmission of Lyα from UV Bright Galaxies at z \gtrsim 7

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Abstract

Recent detections of Lyman alpha (Lyα) emission from z > 7.5 galaxies were somewhat unexpected given a dearth of previous non-detections in this era when the intergalactic medium (IGM) is still highly neutral. But these detections were from UV bright galaxies, which preferentially live in overdensities that reionize early, and have significantly Doppler-shifted Lyα line profiles emerging from their interstellar media (ISM), making them less affected by the global IGM state. Using a combination of reionization simulations and empirical ISM models we show, as a result of these two effects, that UV bright galaxies in overdensities have \( z > 2 \times \) higher transmission through the \( z \sim 7 \) IGM than typical field galaxies, and that this boosted transmission is enhanced as the neutral fraction increases. The boosted transmission is not sufficient to explain the observed high Lyα fraction of \( M_{UV} \lesssim -22 \) galaxies, suggesting that Lyα emitted by these galaxies must be stronger than expected due to enhanced production and/or selection effects. Despite the bias of UV bright galaxies to reside in overdensities we show Lyα observations of such galaxies can accurately measure the global neutral hydrogen fraction, particularly when Lyα from UV faint galaxies is extinguished, making them ideal candidates for spectroscopic follow-up into the cosmic Dark Ages.

Key words: dark ages, reionization, first stars – galaxies: evolution – galaxies: high-redshift – intergalactic medium

1. Introduction

Reionization of hydrogen in the universe’s first billion years was driven by the first sources of light. Accurately measuring the timeline of reionization, i.e., average neutral hydrogen fraction (\( \xi_{HI} \)) as a function of redshift, enables us to infer properties of these sources. Lyman alpha (Lyα) emission from galaxies has long been touted as a tracer of \( \xi_{HI} \) during reionization: Lyα photons are absorbed by neutral hydrogen (e., Dijkstra 2014).

The rapidly declining fraction of Lyman-break galaxies (LBGs) emitting Lyα at \( z > 6 \) (e., Fontana et al. 2010; Stark et al. 2010; Treu et al. 2013; Pentericci et al. 2014; Schenker et al. 2014; Mason et al. 2018) and strong damping wing absorption of \( z \sim 7 \) quasar spectra (Greig et al. 2016; Bañados et al. 2017) suggest that the universe is significantly neutral at \( z \gtrsim 7 \). Recent detections of Lyα from galaxies at \( z > 7.5 \) (Oesch et al. 2015; Zitrin et al. 2015; Roberts-Borsani et al. 2016; Stark et al. 2017) are therefore surprising. Furthermore, these detections come from \( M_{UV} \lesssim -22 \) galaxies (\( \gtrsim 2.5 L^* \)). At lower redshifts UV bright galaxies are least likely to have strong Lyα (e., Stark et al. 2010). Why can we see Lyα from these galaxies?

Reionization is likely highly inhomogeneous—overdense regions reionize more rapidly as they are filled with many ionizing sources (e., McQuinn et al. 2007). The brightest galaxies likely reside in overdensities (e., Trenti et al. 2012; Barone-Nugent et al. 2014; Castellano et al. 2016). How easily are Lyα photons from such galaxies in overdensities transmitted through the intergalactic medium (IGM), compared to field galaxies? How does the interstellar medium (ISM) radiative transfer of Lyα affect its IGM transmission (Figure 1)? Can these biased galaxies still measure \( \xi_{HI} \)?

Here we combine cosmological reionization simulations with empirical models of galaxy properties to understand the transmission of Lyα from UV bright galaxies. We describe our combination of simulations and empirical models in Section 2. In Section 3 we present our results on the evolving transmission of Lyα emission from galaxies in massive halos, the interpretation of the observed “Lyα fraction,” and the efficacy of UV bright galaxies as probes of \( \xi_{HI} \). We discuss our results in Section 4 and summarize in Section 5.

We use the Planck Collaboration et al. (2015) cosmology. All magnitudes are in the AB system.

2. Method

To model the transmission of Lyα photons from galaxies through the reionizing IGM we combine the public Evolution of Structure simulations (EoS,\textsuperscript{9} Mesinger et al. 2016) with empirical models of galaxy properties. We follow the method of Mason et al. (2018; hereafter M18) and refer the reader there for more details. We describe our methods briefly below.

The EoS simulations treat inhomogeneous recombinations and ionizations at a sub-grid level on a density field in a 1024\(^3\) box with sides 1.6 Gpc. The simulations have two runs to

\textsuperscript{9} http://homepage.sns.it/mesinger/EOS.html
Figure 1. Left: UV bright galaxies (large stars) preferentially live in overdensities, which reionize early (green regions). Lyα damping wing optical depths are dominated by the distance to the first neutral patch (white regions) that photons encounter, \(d_{HI}\), thus UV bright galaxies have a higher average Lyα transmission than UV faint galaxies (small stars) as they live further from neutral patches. The sightline-to-sightline scatter of Lyα transmissions for UV bright galaxies is lower due to lower scatter in \(d_{HI}\) (orange arrows for UV bright galaxies, blue arrows for UV faint galaxies). Right: gas and dust resonantly scatter and absorb Lyα photons inside galaxies. Lyα emitted (dashed lines) by UV bright galaxies (orange) is usually more Doppler-shifted than Lyα from UV faint galaxies (blue), as they contain more gas and dust. Damping wing absorption during reionization attenuates Lyα smoothly with wavelength/velocity offset (gray line—example shown is \(\Delta v = 0.66\)), so Lyα transmitted (solid lines) through the IGM depends on galaxy properties.

where \(J_\alpha(\Delta v, M_h, v)\) is the normalized Lyα lineshape emitted from galaxies. We model circumbulgal medium (CGM) absorption by truncating the lineprofiles at the halo circular velocity. As we are only interested in the differential evolution of EW, this is valid assuming the only significant change in the optical depth to Lyα between \(z \sim 6\) and \(z \sim 7\) is due to reionization. We discuss the impact of an evolving CGM in Section 4.

We calculate \(T_{\text{CGM}}\) for millions of realizations of model galaxies along thousands of sightlines in 40 \(z = 7\) IGM simulation cubes with average neutral fractions \(0 \leq \langle x_{HI}\rangle \leq 0.95\) \(\langle \Delta \tau_{HI}\rangle \sim 0.02\) to generate \(p(T_{\text{CGM}}x_{HI}, M_h)\) and forward-model the observed \(p(\text{EW}_{\text{Ly}α})\).

3. Results

Here we describe the key results of our study: Lyα from UV bright galaxies in massive halos can have high transmission through the IGM, even in a highly neutral universe (Section 3.1); our model is consistent with the observed evolution of the Lyα fraction, except for extremely bright galaxies \((M_{UV} \lesssim -22)\) that must have higher than expected emitted Lyα EWs (Section 3.2); and UV bright galaxies can measure \(x_{HI}\) if their emitted Lyα EW distribution is known (Section 3.3).

3.1. Boosted Transmission of Lyα from Massive Halos

To explore the differences between the most biased galaxies and the bulk of the high-redshift galaxy population we examine \(p(T_{\text{CGM}})\) in two halo mass bins: \(10^{11.5} \leq M_h \leq 10^{12} M_\odot\) (57 sightlines in the EoS simulations, hosting \(M_{UV} \lesssim -21\) galaxies) and \(10^{10} \leq M_h \leq 10^{11} (\sim 10^4\) sightlines, \(M_{\text{UV}} \gtrsim 19.5\) galaxies, comparable to the faintest \(z > 6\) LBGs with detected Lyα, e.g., Huang et al. 2016; Hoag et al. 2017).

Figure 2 shows \(p(T_{\text{CGM}}x_{HI}, M_h)\), using three models for Lyα velocity offsets: (1) drawn from the M18 \(p(\Delta v|M_h)\) model, low-mass halos have median \(\Delta v \sim 90\) km s\(^{-1}\), high-mass halos...
Figure 2. \( \text{Ly}\alpha \) transmission fraction distributions, \( p(T_{\text{IGM}}|X_{\text{HI}}) \) at a given \( X_{\text{HI}} \). Highest density/darkest regions correspond to most likely values of \( T_{\text{IGM}} \) at each \( X_{\text{HI}} \). We show \( p(T_{\text{IGM}}) \) in two mass bins (\( 10^{11.5} \leq M_h \leq 10^{12} M_\odot \), left; \( 10^{10} \leq M_h \leq 10^{11} M_\odot \), right). We use three models for emitted \( \text{Ly}\alpha \) lines: (upper panels) the mass-dependent model presented by M18, with high-mass halos having higher \( \Delta v \) (middle) \( \Delta v = 200 \text{ km s}^{-1} \); (lower) \( \Delta v = 50 \text{ km s}^{-1} \). With mass-dependent velocity offsets \( T_{\text{IGM}} \) is boosted for high-mass halos.

have median \( \Delta v \approx 220 \text{ km s}^{-1} \), (2) \( \Delta v = 200 \text{ km s}^{-1} \), often the fiducial value used in reionization \( \text{Ly}\alpha \) modeling (e.g., Dijkstra et al. 2011; Mesinger et al. 2015), (3) \( \Delta v = 50 \text{ km s}^{-1} \).

Irrespective of emitted line properties, galaxies in massive halos have higher \( T_{\text{IGM}} \) as they preferentially live in overdensities that reionize early (e.g., McQuinn et al. 2007), so their \( \text{Ly}\alpha \) photons are redshifted into the flattest part of the damping wing (Figure 1) by the time they reach cosmic neutral patches. Mass-dependent velocity offsets enhance this effect: \( \text{Ly}\alpha \) from low-mass halos is more easily attenuated as they have low \( \Delta v \), whereas \( T_{\text{IGM}} \) from massive halos is boosted.

The scatter in \( T_{\text{IGM}} \) is lower for massive halos: the smaller scatter in distance from source galaxies to the first neutral patch (Figure 1) reduces the sightline-to-sightline variation in optical depths. This makes galaxies in massive halos accurate probes of \( X_{\text{HI}} \). The effect is most pronounced for \( 0.3 \lesssim X_{\text{HI}} \lesssim 0.6 \), when neutral patches are narrower and more widely separated (Mesinger & Furlanetto 2008). As noted by Mesinger & Furlanetto (2008; though in the context of quasars), if halo masses can be estimated for galaxies the accuracy in \( X_{\text{HI}} \) increases.

The top panel of Figure 3 investigates contributions to \( T_{\text{IGM}} \). We compare \( T_{\text{IGM}} \) from galaxies in low-mass and high-mass halos, with fixed low or high \( \Delta v \), to galaxies in low-mass halos with low \( \Delta v \). Massive halos always have high \( T_{\text{IGM}} \), as they reside in larger ionized bubbles, indicating halo mass is the dominant cause of high transmission. When \( \text{Ly}\alpha \) is emitted at high \( \Delta v \), \( T_{\text{IGM}} \) is significantly boosted for massive halos. In the very early stages of reionization \( T_{\text{IGM}} \) is boosted for low-mass halos with high \( \Delta v \) compared to low \( \Delta v \), massive halos, likely because ionized bubbles around massive halos are still small.

The lower panel of Figure 3 shows a realistic estimate of the boosting, using mass-dependent \( \Delta v \) (comparing the top panels of Figure 2). For \( X_{\text{HI}} > 0.6 \) \( T_{\text{IGM}} \) for massive halos are \( >2 \times \) higher than for low-mass halos, rising to a factor \( \sim 10 \) for \( X_{\text{HI}} > 0.9 \). We compare the transmission ratio for the two EoS
simulations: FAINT GALAXIES and BRIGHT GALAXIES (Section 2). The transmission boost is comparable; this effect is relatively independent of the timeline and morphology of reionization. We use these realistic $T_{\text{IGM}}$ for UV bright galaxies in the next sections.

### 3.2. Evolving Ly$\alpha$ Fraction for UV Bright Galaxies

An increasing fraction of Ly$\alpha$ emitters (EW $> 25$ Å) is observed in the LBG population over $2 \lesssim z \lesssim 6$ (e.g., Stark et al. 2010; Cassata et al. 2015), likely due to decreasing dust in galaxies (Hayes et al. 2011). A drop in the Ly$\alpha$ fraction at $z > 6$ is usually attributed to absorption by an increasingly neutral IGM during reionization (see Dijkstra 2014 for a recent review).

Figure 4 (right panel) shows the $4 \leq z \leq 8$ Ly$\alpha$ fraction for UV bright galaxies. At $z < 6$ the observations are consistent, but at $z \geq 6$ the Ly$\alpha$ fraction measured for samples with $M_{\text{UV}} \lesssim -21.5$ (Curtis-Lake et al. 2012; Stark et al. 2017) is significantly higher than for those at lower luminosities. Much of this discrepancy may be due to selection effects: using only the $z_{850}$-band for LBG selection the Curtis-Lake et al. (2012) sample could be biased toward strong Ly$\alpha$ emission (De Barros et al. 2017), and the Stark et al. (2017) sample was selected via red Spitzer/IRAC [3.6]–[4.5] colors (Roberts-Borsani et al. 2016) making them likely strong [O III]$+\text{H}$ß emitters, requiring hard radiation fields and young stellar populations, which increase Ly$\alpha$ production and escape (Finkelstein et al. 2013; Zitrin et al. 2015). Using our model we test how the boosted $T_{\text{IGM}}$ for galaxies in massive halos (Section 3.1) contributes to their Ly$\alpha$ emitter fraction.

We plot the evolution allowed by the M18 $z \sim 7$ neutral fraction estimate ($\alpha_{\text{T,M18}} = 0.59^{+0.15}_{-0.13}$) for galaxies in massive halos, using the maximum transmission demonstrated in Figure 2 (top left panel). We forward-model $p(\text{EW}_{\text{Ly} \alpha})$ by convolving $p(T_{\text{IGM}})$ with the UV magnitude-dependent $p(\text{EW}_{\text{Ly} \alpha}^\text{emit})$ described in Section 2. $p(\text{EW}_{\text{Ly} \alpha}^\text{emit})$ is a major uncertainty, so we use a range of distributions: LOW-EW, MID-EW, and HIGH-EW, corresponding to the measured $z \sim 6$ distributions for LBGs with $M_{\text{UV}} \sim [-21, -20.5, -20]$, which bracket the EW variation in the De Barros et al. (2017) sample (Figure 4, left panel). Based on $z \leq 6$ observations we expect UV bright galaxies to have LOW-EW or MID-EW distributions.

The observed evolution of the Ly$\alpha$ fraction for $M_{\text{UV}} > -21.5$ samples is consistent with negligible evolution in $p(\text{EW}_{\text{Ly} \alpha}^\text{emit})$. The HIGH-EW distribution is required to be consistent with the Stark et al. (2017) Ly$\alpha$ fraction error region, which is unexpected given that UV bright galaxies at lower redshifts tend to have low Ly$\alpha$ EWs (e.g., Stark et al. 2010).

### 3.3. UV Bright Galaxies as Probes of Reionization

To test the efficacy of UV bright galaxies as probes of reionization we perform a Bayesian inference to obtain the posterior distribution of the neutral fraction given simulated observations of galaxies with Ly$\alpha$ EW and $M_{\text{UV}}$ measurements: $p(\alpha_{\text{T}} \mid \mathbf{W}_{\text{obs}})$, with the samples' median $M_{\text{UV}}$ indicated by color. Shaded regions show the range of evolution allowed by the M18 $\alpha_{\text{T}}$ constraints ($16\%–84\%$ range), for a given model $p(\text{EW}_{\text{Ly} \alpha})$. Hashed regions indicate the allowed evolution to $z = 8$, assuming that $\alpha_{\text{T}}$ does not increase.

We follow the method described by M18 and generate the likelihood of observing a given EW: $p(\text{EW}_{\text{Ly} \alpha}^\text{obs})$. We perform the inference using these likelihoods for in the range of halo masses, we include some scatter in $p(\text{EW}_{\text{Ly} \alpha})$ from De Barros et al. (2017). Using Bayes’ theorem this posterior is proportional to $\int p(\text{EW}_{\text{Ly} \alpha}^\text{obs}) \times p(\alpha_{\text{T}})$, assuming that the observations are independent.

We convolve the high halo mass $p(T_{\text{IGM}})$, described in Section 3.1, with a distribution of emitted EWs. For this work we consider $M_{\text{UV}} = -22$ galaxies. By assigning galaxies to a range of halo masses, we include some scatter in $M_{\text{UV}}$ (e.g., Finkelstein et al. 2015). To generate mock observations, we draw EW values from a likelihood for a given $\alpha_{\text{T}}$, convolve with a $5$ Å uncertainty and treat galaxies with EW $< 15$ Å as non-detections (which are robustly accounted for in the inference). We perform the inference using these mock observations.

Figure 5 shows the posteriors obtained using a simulated sample of 100 UV bright galaxies for a grid of input $\alpha_{\text{T}}$ values.
The inferred posteriors are consistent with the input values over the entire range within the 16%–84% region, showing that UV bright galaxies can be accurate tracers of the average IGM state. We note that our posteriors are broad ($\Delta x_{\rm HI} \sim 0.4$) compared to those obtained using fainter galaxies (c.f. $\Delta x_{\rm HI} \sim 0.25$ in M18). This uncertainty is driven by the shape of $p(\mathrm{EW}_{\lambda_{\alpha}})$, which declines with increasing EW. Reionization further kills the high EW tail of the distribution, making high EW objects rare.

4. Discussion

We have shown that UV bright galaxies in high-mass halos can be precise probes of reionization and are increasingly valuable in reionization’s early stages when $\lambda_{\alpha}$ in UV faint galaxies, emitted close to systemic velocity, is overwhelmingly absorbed in the IGM. However, there are two limitations to using such galaxies to probe reionization: (1) they are rare; (2) they emit less $\lambda_{\alpha}$ due to absorption in their dense ISM. Below we discuss prospects for overcoming these limitations.

Wide-area photometric surveys such as the Brightest of Reionizing Galaxies survey (BoRG; Trenti et al. 2011), UltraVISTA and UDS (e.g., Bowler et al. 2015), and GOLDRUSH (Ono et al. 2018) have discovered $\sim$100 $z \gtrsim 7$ $M_{\odot} < 10^{14}$ LBGs in $\sim$100 deg$^2$. Future wide-area surveys with e.g., WFIRST (Spergel et al. 2013) and Euclid (Laureijs et al. 2011) will likely increase this by a factor $\gtrsim 100$ in $>15,000$ deg$^2$. These sources will be ideal candidates for spectroscopic follow-up to measure the $\lambda_{\alpha}$ EW distribution needed to infer the neutral fraction.

Do UV bright galaxies emit less $\lambda_{\alpha}$? While most $z \lesssim 6$ observations indicate that they do (e.g., Verhamme et al. 2008; Stark et al. 2010), our results suggest the $z \sim 8$ galaxies presented by Stark et al. (2017) must have high intrinsic $\lambda_{\alpha}$ EW. Recent observations of a $M_{\odot} \sim 10^{14}$ galaxy after reionization at $z \sim 4$ detected $\lambda_{\alpha}$ emission with low $\Delta V$ and Lyman continuum radiation (Vanzella et al. 2017), suggesting significantly ionized pathways through the ISM and/or CGM from such galaxies. If these galaxies are efficient producers of ionizing radiation, they may also increase their local ionization field to boost $\lambda_{\alpha}$ transmission through the CGM/IGM.

A holistic understanding of $\lambda_{\alpha}$ emission as a function of redshift and galaxy properties is therefore crucial to improve the use of $\lambda_{\alpha}$ as a cosmological tool. These measurements are becoming increasingly feasible with multi-wavelength observations of LBGs, and time should be invested in establishing $\lambda_{\alpha}$ emission properties over a wide redshift and galaxy mass/UV magnitude range, both in wide areas, and in deep lensed fields with the Hubble Space Telescope (HST; e.g., Treu et al. 2015; Schmidt et al. 2016) and in the near future with the James Webb Space Telescope (JWST; Treu et al. 2017). Better measurements of these properties will enable us to disentangle IGM, CGM, and ISM effects.

5. Summary and Conclusions

We have investigated the IGM transmission of $\lambda_{\alpha}$ from UV bright galaxies during the Epoch of Reionization by combining reionization simulations and empirical relations for galaxy and $\lambda_{\alpha}$ properties. Our main conclusions are as follows.

(i) $\lambda_{\alpha}$ emitted by UV bright galaxies in massive halos has a higher mean and lower dispersion in IGM transmission than $\lambda_{\alpha}$ from typical field galaxies in low-mass halos. This is primarily due to massive halos predominantly residing in overdensities that reionize early, and boosted by their higher $\lambda_{\alpha}$ velocity offsets, reducing damping wing absorption by cosmic neutral hydrogen.

(ii) This boosted transmission is not sufficient to explain the observed evolution of the $6 \lesssim z \lesssim 8$ $\lambda_{\alpha}$ fraction for extremely UV bright galaxies (Stark et al. 2017), suggesting that these objects have higher emitted $\lambda_{\alpha}$ EW than expected.

(iii) With sufficient numbers, the observed $\lambda_{\alpha}$ EW distribution of UV bright galaxies can place tight constraints on the IGM neutral fraction during reionization, and may be the only way to probe the IGM at $z > 7$ when quasars are exceedingly rare and $\lambda_{\alpha}$ from most UV faint galaxies is extinguished.

More comprehensive measurements of the $\lambda_{\alpha}$ EW distribution as a function of redshift and galaxy properties are necessary to understand the evolving visibility of $\lambda_{\alpha}$ emission and to disentangle the effects of the ISM and IGM during reionization. Current and upcoming spectroscopic observations have the ability to do this and to increase the efficacy of $\lambda_{\alpha}$ as a cosmological tool.

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**Software:** IPython (Pérez & Granger 2007), matplotlib (Hunter 2007), NumPy (Van Der Walt et al. 2011), and EMCEE (Foreman-Mackey et al. 2013).

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