CONSTRaining REIONIZATION WITh THE EVOLUTION OF THE LUMINOSITY FUNCTION OF Ly$\alpha$ EMITTING GALAXIES

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ABSTRACT

At redshifts beyond $z \gtrsim 6$, as the mean fraction of neutral hydrogen $\langle x_{\text{H}} \rangle$ in the intergalactic medium (IGM) increases, the line flux of Ly$\alpha$ emitters can be significantly attenuated, which can result in a decrease in the observed number of emitters at a given Ly$\alpha$ flux. However, cosmological H ii regions surrounding the Ly$\alpha$ emitting galaxies alleviate these effects. We use simple models of the Ly$\alpha$ line attenuation that incorporate the presence of H ii regions to predict the overall effect of the Ly$\alpha$ absorption on the Ly$\alpha$ luminosity function (LF). We find, in agreement with other recent studies, that a fully neutral IGM is inconsistent with the Ly$\alpha$ LF remaining unchanged from $z = 5.7$ to $z = 6.5$, as suggested by recent observations. However, the presence of local H ii regions prohibits placing a tight constraint on the mean neutral fraction. We find $\langle x_{\text{H}} \rangle \lesssim 0.25$; the presence of strong winds and/or the clustering of ionizing sources would further weaken this constraint. We conclude that the evolution of the Ly$\alpha$ LF is consistent with reionization occurring near this redshift, as suggested by other observations. Finally, we suggest that a measurement of observed Ly$\alpha$ line width as a function of the Ly$\alpha$ luminosity, in a future, larger sample of Ly$\alpha$ emitters, may serve as a robust diagnostic of the neutral fraction in the IGM.

Subject heading: cosmology: theory — early universe — galaxies: formation — galaxies: high-redshift — quasars: absorption lines — quasars: general

1. INTRODUCTION

The recent detection of Gunn-Peterson (GP; Gunn & Peterson 1965) troughs in the spectra of the Sloan Digital Sky Survey (SDSS) quasars (Becker et al. 2001; White et al. 2003) places a relatively direct lower limit on the mean (volume-averaged) neutral fraction of the intergalactic medium (IGM) at $z \sim 6$. While this limit is relatively weak, $\langle x_{\text{H}} \rangle \gtrsim 10^{-3}$, the spectral imprint (Mesinger & Haiman 2004) and size (Wyithe & Loeb 2004) of cosmological H ii regions around the SDSS quasars indicate that the neutral fraction around $z \sim 6$ is significantly higher, $\langle x_{\text{H}} \rangle \gtrsim 0.1$. The rapid evolution of $\langle x_{\text{H}} \rangle$ with redshift, inferred from the spectra of several quasars at $5.5 \lesssim z \lesssim 6.5$ (Fan et al. 2002; Cen & McDonald 2002; Lidz et al. 2002; but see Songaila 2004), and also the thermal state of the IGM at $3 \lesssim z \lesssim 4$ (Hui & Haiman 2003; Theuns et al. 2002), indicate that a percolation of discrete H ii regions is occurring around this epoch.

Ly$\alpha$ emission lines from high-redshift sources can serve as another probe of the ionization state of the IGM. The damping wing of the GP absorption from the IGM can cause a characteristic absorption feature (Miralda-Escudé 1998). In a significantly neutral IGM, the absorption can produce conspicuous effects, i.e., attenuating the emission line, making it asymmetric, and shifting its apparent peak to longer wavelengths (Haiman 2002; Santos 2004). These effects generally increase with $\langle x_{\text{H}} \rangle$, and it has been suggested that a strong drop in the abundance of Ly$\alpha$ emitters beyond the reionization redshift can serve as a diagnostic of a nearly neutral IGM (Haiman & Spaans 1999; Rhoads & Malhotra 2001). Recently, Malhotra & Rhoads (2004, hereafter MR04) and Stern et al. (2005) carried out the first application of this technique by comparing the luminosity functions (LFs) of Ly$\alpha$ emitters at $z = 5.7$ and 6.5. The LF shows no evolution in this range, and this has been interpreted as evidence against percolation taking place near $z \sim 6$.

A potential caveat for this interpretation is that $z \sim 6$ galaxies are surrounded by their own local cosmological H ii regions, which can significantly reduce the attenuation of the Ly$\alpha$ line flux (Cen & Haiman 2000; Madau & Rees 2000). It has been shown that this can render Ly$\alpha$ lines detectable even if the galaxies are embedded in a fully neutral IGM (Haiman 2002; Santos 2004; Mesinger et al. 2004), especially when the increased transmission due to the clustering of ionizing sources is taken into account (Furlanetto et al. 2004; Gnedin & Prada 2004; Wyithe & Loeb 2005) and/or if the Ly$\alpha$ emission has a significant recession velocity with respect to the absorbing gas.

In this paper, we study the impact of IGM absorption on the Ly$\alpha$ LF, assuming that the unobscured Ly$\alpha$ LF remains unchanged from $z = 5.7$ to $z = 6.5$. Our analysis is similar to that in the recent study by MR04. The two main differences are that (1) we explicitly compute an upper limit on the neutral fraction (whereas MR04 demonstrated only that a fully neutral IGM is ruled out), and (2) we model the attenuation of Ly$\alpha$ lines including cosmological H ii regions. In agreement with MR04, we find that very little attenuation (by a factor of $\lesssim 2$) can be tolerated by the lack of evolution of the LF over the range $5.7 \lesssim z \lesssim 6.5$, and that $\langle x_{\text{H}} \rangle \approx 1$ can be ruled out even in the presence of the H ii regions. We find, however, that the presence of local H ii regions allows a neutral fraction as high as $\langle x_{\text{H}} \rangle \approx 0.25$. We also show that $\langle x_{\text{H}} \rangle \sim 1$ may be allowed only if the ionizing sources were unexpectedly strongly clustered. In either case, we argue that the present Ly$\alpha$ LFs are consistent with reionization occurring near $z \sim 6$.

1 Throughout this paper we assume a cold dark matter cosmology (LCDM), with $\Omega_m = 0.73$, $\Omega_{\Lambda} = 0.27$, $\Omega_b = 0.044$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, consistent with the recent results from WMAP (Spergel et al. 2003). Unless stated otherwise, all lengths are quoted in comoving units.
2. THE OBSERVED Lyα LF

Following MR04, we take as basic inputs to our analysis the Lyα LFs at $z = 5.7$ and 6.5. We adopt the forms of the LF at these two redshifts from MR04. Note that at both redshifts, the LFs are inferred by culling several independent data sets (Hu et al. 2002; Rhoads et al. 2003; Kodaira et al. 2003; Kurk et al. 2004; Tran et al. 2004; Taniguchi et al. 2005). At the $z = 5.7$, the LF is comparatively well determined and well fit by a Schechter function with relatively small errors in normalization ($\Phi_e$) and characteristic luminosity ($L_*$), while the faint-end slope ($\alpha$) is less well determined. Here we adopt the best-fit values of $\Phi_e = 10^{-4} \text{Mpc}^{-3}$, $L_* = 10^{46} \text{ergs s}^{-1}$, and $\alpha = -1.5$, shown by the short-dashed curve in Figure 1. Within the uncertainties quoted in MR04, the values of these parameters do not significantly change our conclusions below.

At $z = 6.5$, the LF is less well determined, as shown by four data points with errors, in Figure 1. Of these four data points, the most constraining is from the deep Subaru field, which reveals the presence of a handful of emitters at $z \sim 6.5$ (Kodaira et al. 2003) and has the smallest error bar. The single, faint lensed galaxy at this redshift found by Hu et al. (2002; represented by the lowest-luminosity point in Fig. 1) implies a surprisingly high abundance of the faintest emitters, but with a single source, it has a large uncertainty. Finally, we follow MR04 and conservatively assume that the intrinsic LF (i.e., prior to processing of the line through the IGM) is the same at $z = 6.5$ as at $z = 5.7$. More realistic models, based on the hierarchical growth of structures, combined with Lyα line processing by gas and dust inside the galaxies, predict that the number of emitters were smaller at earlier epochs (Haiman & Spaans 1999; Le Delliou et al. 2005), which would strengthen the limits on $\langle x_{H\alpha} \rangle$, as seen below.

3. THE ATTENUATION OF Lyα EMISSION LINES

We follow Cen & Haiman (2000) and use a simple model to find the attenuation of the Lyα line as a function of wavelength. The model is straightforward, and we only briefly recap the main features. We start with a Gaussian emission line originating at $z_s = 6.5$, with a line width of $\Delta v = 300 \text{ km s}^{-1}$, typical of normal galaxies (narrower lines would be attenuated more severely; see discussion below). We assume that the source is surrounded by a spherical Strömgren sphere that propagated into the IGM with a neutral fraction $\langle x_{\text{ion}} \rangle$. The IGM is assumed to have a clumpiness factor $C \equiv \langle \rho^2 \rangle / \langle \rho \rangle^2 = 10$ with a lognormal distribution. We assume the presence of a uniform ionizing background, characterized by an ionizing rate $\Gamma_{12}$ (ionizations per $10^{12} \text{ s per atom}$), yielding the given value of $\langle x_{\text{ion}} \rangle$ in ionization equilibrium for the IGM.

We assume a Salpeter initial mass function (IMF), a relation (Charlot & Fall 1993) between star formation rate (SFR) and Lyα luminosity [SFR $= 1 M_\odot \text{ yr}^{-1} \rightarrow L(\text{Ly}\alpha) = 10^{42} \text{ erg s}^{-1}$], and the production of 4000 ionizing photons per proton cycled through a star. We assume $f_{\text{esc}} = 1$ (escape fraction of ionizing radiation) in computing $R_*$, and a lifetime $t_s = 10^8 \text{ yr}$ for each source. These choices are conservative, in that a lower $f_{\text{esc}}$ or a shorter lifetime would tighten the limits on the neutral fraction we derive below. Strictly, $f_{\text{esc}} = 1$ is an assumption that is inconsistent with the presence of the Lyα emission line and should be considered an upper limit on the ionizing luminosity. The lifetime $t_s = 10^8 \text{ yr}$ is consistent with the inferred ages of starburst galaxies at lower redshifts, and in models where Lyα emitters are associated with dark matter halos (Haiman & Spaans 1999), it gives a reasonable fraction of the baryon content of each halo turning into stars. Below we address uncertainties in these parameters by considering an alternative model with the ionizing luminosity reduced by a factor of 10. With all other parameters in the model fixed, we vary $\Gamma_{12}$ (or equivalently $\langle x_{\text{ion}} \rangle$) and compute the factor by which the total line flux is attenuated relative to the unabsorbed Gaussian line. This factor is shown in Figure 2 as a function of the intrinsic luminosity of the source; as expected, faint sources are more severely attenuated.

The attenuation factors in Figure 2 are computed by assuming that the H II regions are being created by a single ionizing source (the Lyα emitter itself). These H II regions (with typical sizes of a few Mpc in the observed range of source luminosities)
may contain many other undetected galaxies, which make the 
H ii regions larger (Furlanetto et al. 2004; Gnedin & Prada 2004; Wyithe & Loeb 2005) and also more highly ionized. Therefore, the results shown in Figure 2 should be viewed as conservative upper limits. These results show that the H ii regions of individual galaxies can significantly reduce the attenuation, especially for relatively bright sources.

4. THE IMPACT ON THE Lyα LF

Next, we use the attenuation factors computed above and obtain the reduction in the cumulative Lyα LF. The resulting LF is shown in Figure 1, for three values of \( \langle x_{HI} \rangle \), 0, 0.1, and 1 (top to bottom). The plot also shows the data for the \( z = 6.5 \) LF with error bars (from MR04). The short-dashed curve is a reproduction of the \( z = 5.7 \) LF (a Schechter function), which, by assumption, would be identical to the \( z = 6.5 \) LF if the IGM contained no neutral H ii.

Note that the attenuation of the line flux depends on the luminosity of the source, but the LF is suppressed by a nearly constant factor (i.e., shifted vertically downward in Figure 1). This is because the LF is steeper at the bright end, which compensates for the reduced effect of line attenuation. The two effects conspire to give a nearly constant reduction of the cumulative LF. If the dependence of the attenuation on the luminosity were different from our model shown in Figure 2 (e.g., due to a variation of \( t_e \) and/or \( \Omega_{esc} \) with luminosity), this conclusion would no longer hold, and the attenuation could also modify the shape of the LF.

5. RESULTS AND DISCUSSION

We can now assign a likelihood to each value of \( \langle x_{HI} \rangle \) by comparing the model LFs and the data shown in Figure 1. For each value of \( \langle x_{HI} \rangle \), we obtain the mean expected number of Lyα emitters above the flux thresholds shown by the data points (here we use the effective volume probed by each survey, listed in Table 2 of MR04). We assume Poisson fluctuations to compute the likelihood in each bin. We find that the lowest-luminosity data point has an a priori Poisson likelihood that is exceedingly low, even in a fully ionized universe. As Figure 1 shows, \( \leq 0.03 \) objects are expected in the small survey volume in which the single-lensed Lyα emitter, represented by this data point, was discovered. However, the lensing configuration for this object is not well constrained, making it difficult to estimate the effective survey volume. We therefore follow MR04 and omit this source from our analysis. The result, i.e., the product of the Poisson probabilities for the three higher-luminosity bins, is shown in Figure 3 as a function of \( \langle x_{HI} \rangle \).

First, the horizontal long-dashed curve shows the likelihood of the fit in the limit of no H i absorption, which yields \( \approx 0.14 \). This shows that the Schechter function that best fits the \( z = 5.7 \) data is also an acceptable fit to the \( z = 6.5 \) data (see MR04 for a demonstration of this point by more elaborate Monte Carlo simulations). The upper solid curve corresponds to our fiducial model and considers various levels of additional obscuration at \( z = 6.5 \). In this model, we find that \( \langle x_{HI} \rangle = 1 \) is ruled out at high significance, in agreement with the conclusions reached by MR04 and Stern et al. (2005; but see discussion below). On the other hand, at the 99.7% confidence level, we find only the relatively weak constraint \( \langle x_{HI} \rangle < 0.25 \). The lower curve corresponds to an alternative model, in which the ionizing luminosity of each galaxy is reduced by a factor of 10 (as would be required if the escape fraction were \( f_{esc} \sim 10\% \) or the lifetime \( t_e \sim 10^7 \) yr. In this case, the upper limit is strengthened to \( \langle x_{HI} \rangle < 0.06 \).

Finally, in order to directly compare our results to those of MR04, we have computed the likelihood of a model with a constant attenuation by a factor of 3 (hypothesis B of MR04). We find a likelihood of \( 2 \times 10^{-3} \), which confirms the MR04 discovery that this model can be rejected at high significance. As Figure 2 shows, this level of attenuation is consistent with our model for bright sources with \( L(\text{Ly} \alpha) = 10^{43} \) ergs sec \(^{-1} \), but is about a factor of 2 too low for sources with \( L(\text{Ly} \alpha) = 10^{42} \) ergs sec \(^{-1} \). The constant attenuation case could be physically realized if the ionizing luminosities of all Lyα emitters (regardless of Lyα luminosity) were similar (a weak monotonic dependence would be required if brighter galaxies had broader emission lines, which would suffer a larger attenuation for a fixed ionizing luminosity).

As mentioned above, H ii regions can be enlarged by the clustering of ionizing sources, and also by their being elongated along our line of sight (e.g., Gnedin & Prada 2004). These effects reduce the Lyα attenuation and weaken the upper limit on \( \langle x_{HI} \rangle \). It is interesting to ask whether any constraint can be placed on the neutral fraction, in the presence of clustering. To address this question, we recomputed the attenuation factors shown in Figure 2, and the implied LFs shown in Figure 1, fixing \( \langle x_{HI} \rangle = 1 \) but boosting the ionizing emissivity of each source by a constant factor of \( B \). We find that the boosting factor required to render this model acceptable at the 99.7% confidence level is approximately \( B = 60 \) (note that the increased luminosity is required to reduce both the GP damping wing and the residual H i inside the H ii region).

In order to assess whether the ionizing emissivity can be boosted by this factor, we computed the total mass in dark matter halos in the mass range \( M_{\text{min}} \) to \( M_{\text{e}} \), and within a sphere of radius \( R \) around a halo of mass \( M_{r} \). We included the spatial correlations between halos with a prescription for linear bias (see eq. [15] in Haiman et al. 2001). For the likely halo mass range of \( 10^{11} M_{\odot} \lesssim M \lesssim 10^{12} M_{\odot} \) (Rhoads et al. 2003) and H ii sphere
Lyα emitters. For faint Lyα emitters, which have small H II regions, the GP trough is close to the wavelength of the line, and the blue half of the emission line is effectively erased. In the remaining red side of the line, the attenuation is dominated by the GP damping wing. On the other hand, for sufficiently bright emitters, some of the flux on the blue side is transmitted. On the blue side of the line, the attenuation is dominated by the residual H I inside their cosmic H II regions. As a result, the line shape is not a monotonic function of the luminosity, since the effects of the residual H I become visible only at large luminosities.

In Figure 4, we show the predicted FWHM of the transmitted line, as a function of Lyα luminosity. The top and bottom panels assume an intrinsic Gaussian line shape with a width of 300 and 30 km s$^{-1}$, respectively. On both panels, the dashed curve assumes an ionizing background of $\Gamma_{12} = 0.1$ (or $\langle x_{HI} \rangle \sim 10^{-3}$), and the three solid curves assume, from top to bottom, $\Gamma_{12} = 0$, 0.0001, and 0.0004 (or $\langle x_{HI} \rangle = 1, 0.5, \text{and} 0.25$). The feature observable at $\sim 10^{41} - 10^{42}$ ergs s$^{-1}$ is unique to a significantly neutral ($\langle x_{HI} \rangle \geq 20\%$) IGM.

Another effect that can further weaken the upper limits on the neutral fraction is a systematic redshift of the Lyα emission lines relative to the absorbing gas. Lyman break galaxies at lower redshift reveal such systematic shift by several hundred km s$^{-1}$, attributed to galactic winds (Shapley et al. 2003). If velocity offsets as high as this are common for Lyα emitters at $z \approx 6$, this would render Lyα line attenuation from the residual H I within the H II region effectively negligible and also significantly reduce the GP damping wing absorption. By repeating our analysis above to obtain a likelihood for a neutral universe, we find that a redshift by 600 km s$^{-1}$ is required for $\langle x_{HI} \rangle = 1$ to yield an acceptable fit for the LF. Shapley et al. (2003) find a decreasing velocity offset with increasing Lyα equivalent width, with $\langle \Delta v \rangle < 500$ km s$^{-1}$ for $W_\alpha > 50$ Å (see their Fig. 11), suggesting that high-z Lyα emitters may not have the requisite 600 km s$^{-1}$ offsets.

Finally, we propose a different diagnostic of the neutral fraction that could be available from a future, larger sample of $z \gtrsim 6$ Lyα emitters.

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