Luminosity Functions of Lyα Emitting Galaxies and Cosmic Reionization of Hydrogen

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ABSTRACT
Recent observations imply that the observed number counts of Lyα emitters (LAEs) evolved significantly between z = 5.7 and z = 6.5. It has been suggested that this was due to a rapid evolution in the ionisation state, and hence transmission of the IGM which caused Lyα flux from z = 6.5 galaxies to be more strongly suppressed. In this paper we consider the joint evolution of the Lyα and UV luminosity functions (LFs) and show that the IGM transmission evolved between z = 6.5 and z = 5.7 by a factor 1.1 < R < 1.8 (95% CL). This result is insensitive to the underlying model of the Lyα LF (as well as cosmic variance). Using a model for IGM transmission, we find that the evolution of the mean IGM density through cosmic expansion alone may result in a value for the ratio of transmissions as high as R = 1.3. Thus, the existing LFs do not provide evidence for overlap. Furthermore, the constraint R < 1.8 suggests that the Universe at z = 6.5 was more than half ionised by volume, i.e. x_e > 0.5.

Key words: cosmology: theory–galaxies: high redshift; statistics

1 INTRODUCTION
Reionization of the Intergalactic Medium (IGM) is one of the milestones in the history of our Universe. Following recombination of the primordial plasma, gas in the Universe remained neutral until it became reionised by the first sources of UV-radiation. The epoch of reionization began with the formation of these first UV-sources, and ended when the entire IGM was cleared of neutral gas. The process of reionization was complex and is not well understood. The nature of the first UV-sources is unknown. Furthermore, various feedback mechanisms, both positive and negative, affect subsequent star, galaxy and black hole formation and hence the later stages of reionization. Extensive modelling, both semi-analytical (e.g. Cen 2003; Wyithe & Loeb 2003, Haiman & Holder 2003) and numerical (e.g. Gnedin 2003; Iliev et al. 2006), has been performed, with the aim of interpreting the few existing observational constraints on reionization (see Fan et al. 2006a, for a review). The detection of flux blueward of the Lyα in high redshift quasars suggests that the Universe is fully ionised at z < 6 (e.g. Fan et al. 2002). At higher redshifts, several Sloan Digital Sky Survey (SDSS) quasars show complete Gunn-Peterson troughs (Fan et al. 2006b). These troughs can be translated into lower limits on the neutral fraction of hydrogen in the IGM, and suggest that reionization may not have been completed until z ≈ 6 (Fan et al. 2002; Lidz et al. 2002; Wyithe & Loeb 2004a; Mesinger & Haiman 2004, 2007). On the other hand, the measurement of optical depth for CMB photons to Thomson scattering by the Wilkinson Microwave Anisotropy Probe (WMAP) (Spergel et al. 2006), implies that the IGM is fully reionised out to z = 12 ± 3 or partially reionised out to even higher redshifts (e.g. Fig 3 of Spergel et al. 2006).

Whether reionization indeed ended at z ~ 6 is still an open question. By adding the derived sizes of HII bubbles surrounding observed z = 6.5 Lyα emitters, Malhotra & Rhoads (2006) have shown that at least 20 – 50% of the volume of the IGM had been reionised by z = 6.5. Becker et al. (2008) suggested that the observed Gunn-Peterson troughs in quasar spectra at z > 6 can be explained without invoking any abrupt changes in the neutral fraction of the IGM (also see Maselli et al. 2007; Bolton & Haehnelt 2007). On the other hand, Kashikawa et al. (2006) have found the Lyα luminosity function (hereafter LF) to evolve between z = 5.7 and z = 6.5. In particular, the z = 6.5 Lyα LF lies significantly below that measured at z = 5.7. Furthermore, Kashikawa et al. (2006) show that the rest frame UV-LF of LAEs does not evolve, within its uncertainties, between z = 5.7 and z = 6.5. These observations are explained naturally, if the flux from z = 6.5 Lyα emitters is attenuated by a larger factor than the flux from emitters at higher z.

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z = 5.7 (Haiman 2002, Santos 2004). The increase in attenuation could be interpreted as sudden change in the intergalactic neutral hydrogen content, which is thought to be a key feature of the end of the reionization epoch. Thus, the Lyα LF could be used to probe the last stages of reionization. In this paper we investigate the constraints that may be placed on the evolution of the IGM transmission using the observed Lyα LF s at z = 5.7 and z = 6.5. As part of our analysis, we also investigate how the rest-frame UV-LF of LAEs may provide additional constraints.

Haiman & Spans (1999) were the first to advocate the use of the Lyα luminosity function to constrain reionization, and several other papers have followed since (e.g. Malhotra & Rhoads 2004; Le Delliou et al. 2005; Haiman & Cen 2005; Le Delliou et al. 2006; Furlanetto et al. 2006; Mao et al. 2006). The work presented in this paper differs from other investigations in two important aspects. Firstly, our model incorporates detailed calculations of the IGM transmission (Dijkstra et al. 2007). For a description of these calculations the reader is referred to that paper. Here, we briefly summarise the models main ingredients. The IGM transmission is calculated using a model for the gas in the IGM that accounts for clumping, and infall. In this model, resonant absorption of Lyα photons by gas in the infall region (which extends out to several virial radii) erases a significant fraction of the Lyα line. The model also accounts for damping wing absorption in cases in which a (partially) neutral IGM surrounds the HII bubble. Secondly, we perform statistical comparisons to the most up-to-date observations.

In §2 we present our model of the Lyα LF. In §3 we describe the data available. The results of our comparison with the data and conclusions are presented in §4 and §5 respectively. The parameters for the background cosmology used throughout this paper are $\Omega_m = 0.24$, $\Omega_{\Lambda} = 0.76$, $\Omega_b = 0.044$, $h = 0.73$ and $\sigma_8 = 0.74$ (Spergel et al. 2006).

2 THE MODEL OF THE LYα LUMINOSITY FUNCTION

We use the following simple prescription to relate the Lyα luminosity of a galaxy to the mass of its host dark matter $M_{\text{tot}}$. The total mass of baryons within a galaxy is $(\Omega_b/\Omega_m)M_{\text{tot}}$, of which a fraction $f_z$ is assumed to be converted into stars over a time scale of $t_{\text{sys}} = \epsilon DC_{\text{halo}}$. Here, $\epsilon_{DC}$ is the duty cycle and $t_{\text{halo}}(z) \equiv \frac{1}{\frac{1}{2}H(z)}$, is the Hubble time at redshift $z$. This prescription yields a star formation rate of $M_z = f_z(\Omega_b/\Omega_m)M_{\text{tot}}/t_{\text{sys}}$. The star formation rate can be converted into a Lyα luminosity by assuming that approximately two-thirds of the ionising photons absorbed within the galaxy are converted into Lyα (Osterbrock 1989), thus $L_{\alpha} = 0.68\nu_{\alpha}(1-f_{\text{esc}})Q_{\alpha}$. Here, $f_{\text{esc}}$ is the escape fraction of ionising photons, $f_{\text{esc}} \ll 1$, and $h_{\alpha} = 10.2$ eV is the energy of a Lyα photon. The total output of ionising photons per unit mass of star formation, $Q_{\alpha}$, depends on the metallicity of the gas from which stars formed, as well as their initial mass function (Kennicutt 1998, Schaerer 2003). In the reminder of this paper, we assume a Salpeter IMF and $Z = 0.05Z_\odot$. The number density of Lyα emitters with Lyα luminosities exceeding $T_{\alpha} \times L_{\alpha}$ is then given by

$$N(> T_{\alpha} \times L_{\alpha}) = \epsilon_{DC} \int_{M_{\alpha}}^{\infty} dM \frac{dn}{dM},$$

where the Lyα luminosity and host halo mass, $M_{\alpha}$, are related by

$$T_{\alpha} \times L_{\alpha} = 2.0 \times 10^{42} \text{ erg s}^{-1} \frac{M_{\alpha}(M_\odot)}{M_{\text{sys}}(\text{yr})} f_{\alpha} T_{\alpha}.$$ (2)

In this relation, $T_{\alpha}$ is the IGM transmission multiplied by the escape fraction of Lyα photons from the galaxy. The function $dn/dM$ is the Press-Schechter (1974) mass function (with the modification of Sheth et al. 2001), which gives the number density of halos of mass $M$ (in units of comoving $\text{Mpc}^{-3}$).

According to this prescription, the Lyα LF has two free parameters ($\epsilon_{DC}, f_{\alpha} T_{\alpha}$). Thus, we explicitly assume that $T_{\alpha}$ is independent of $M_\alpha$ and $M_{\alpha}$. In Dijkstra et al. (2007), we found $T_{\alpha}$ to decrease with increasing $M_\alpha$ (because infall is more prominent around higher mass halos) and increasing $M_{\alpha}$ (because a larger output of ionising photons reduces the impact of resonant absorption in the infall region). Conversely, for a fixed $\epsilon_{DC}$, increasing $M_\alpha$ results in an increase in $M_{\alpha}$, and hence an increase in $T_{\alpha}$. Given that the range of observed luminosities, and hence halo masses, spans only $\sim 1$ dex (§3), the variation in $T_{\alpha}$ with $M_\alpha$ and $M_{\alpha}$ can be ignored. In this paper we compare models for the Lyα LF to observation as a function of these parameters and constrain the evolution in $f_{\alpha} T_{\alpha}$ between $z = 5.7$ and $z = 6.5$.

3 THE DATA

Detailed Lyα LFs have recently been presented by Shimasaku et al. (2006) for LAEs observed at $z = 5.7$, and by Taniguchi et al. (2005) and Kashikawa et al. (2006), for LAEs observed at $z = 6.5$. Some caution must be exercised when comparing our models to this data. First, the observed luminosities have been derived from the observed fluxes by assuming that all Lyα emerging from the galaxy was transmitted by the IGM. However, this is very unlikely. In fact, it has been shown that under reasonable model assumptions, the IGM transmits only a fraction of $T_{\alpha} = 0.1 - 0.3$ (Dijkstra et al. 2007) of Lyα photons, even

\[ 1 \text{ The uncertainty in the relation between Lyα luminosity and } M_{\text{tot}} \text{ is large, as it depends on an unknown IMF and metallicity of the gas from which the galaxies formed (Schaerer 2003). For the present work, because of the degeneracy between } f_{\alpha} \text{ and the prefactor in Eq 2, the exact relation (and therefore the assumed metallicity) is not important.} \]

\[ 2 \text{ Although it is reasonable to assume that the star formation rate and thus Lyα luminosity-in a galaxy is related to the total amount of gas available, and thus to } M_{\text{tot}}, \text{ no direct observational evidence exists to support this assumption. The fact that we obtain good fits to the data for reasonable model parameters (§4) is promising, and suggests that our model provides a reasonable description. However, even if one dismisses the assumption that Lyα luminosity relates to halo mass, then it is still possible to obtain constraints on the change of the IGM transmission with redshift using the rest-frame UV-LF of LAEs (as is discussed in §4.2).} \]
when highly ionised. We therefore replace the quoted observed luminosities, $L_{\text{Ly}\alpha}$ by $\tau_\alpha \times L_{\text{Ly}\alpha}$ (as in Eq.1 and Eq.2). Second, the error bars on the data are uncertain. For example, the open circles shown in our Figure 2 and Figure 5 of Kashikawa et al. (2004) denote the LF derived from the raw counts of their spectroscopic sample - additional photometric sample. The filled circles are corrected for detection incompleteness. The error-bars on the filled circles denote Poisson-errors. Additionally, cosmic variance is expected to add a variance of 30-50% at the lowest (highest) luminosities (e.g. Somerville et al. 2004) and enters as an overall uncertainty that the evolution of the Lyα LF alone, can be fully accounted for by the evolution of the mass function of dark matter halos. In the second part, we remove the effect of cosmic variance by considering the joint evolution of the Lyα and UV-LFs.

Furthermore, the lower luminosity points ($\tau_\alpha L_{\text{Ly}\alpha} \leq 5 \times 10^{42}$ erg s$^{-1}$) suffer more from detection incompleteness, as evidenced by the larger offset between the corrected and uncorrected data points. In addition, the IGM is expected to transmit only 10-40% of the Lyα flux for these galaxies, and the detection of these low luminosity Lyα emitters requires an unusually large IGM transmission ($\tau_\alpha \sim 1$), or unusually large Lyα luminosity (Dijkstra et al. 2007). It follows then that these galaxies must comprise only a (small) subset of the true sample. However, the exact uncertainty this introduces is not known. We account for this uncertainty by enlarging the adopted error-bars at $\tau_\alpha L_{\text{Ly}\alpha} \leq 5 \times 10^{42}$ erg s$^{-1}$ by factors of 4 and 3 for the lowest and second lowest luminosity point, respectively (on the filled circles). These enlargements were chosen so that the 1 – $\sigma$ error bars enclose the data points prior to the adjustment. The choice of error bars on these low luminosity points affects the values of our best fit model parameters, but not our conclusions regarding evolution in transmission of the IGM.

4 RESULTS

We calculated the Lyα LF for a grid of models in the $(\epsilon_{\text{DC}}, f_\alpha, \tau_\alpha)$-plane, and generated likelihoods $L[P] = \exp[-0.5\chi^2]$, where $\chi^2 = \sum_i \frac{(\text{data}_i - \text{model}_i)^2}{\sigma_i^2}$, for each model. Here, data$_i$ and $\sigma_i$ are the $i$th data point and its error, and model$_i$ is the model evaluated at the $i$th luminosity bin. The sum is over $N_{\text{data}} = 6$ points.

Likelihoods were determined for each redshift independently. In the left panel of Figure 4 we show likelihood contours in the $(\epsilon_{\text{DC}}, f_\alpha, \tau_\alpha)$-plane at 64%, 26% and 10% of the peak likelihood at $z = 5.7$ (as dashed contours) and $z = 6.5$ (overlaid as solid contours). The likelihood contours at both redshifts fill the same region of the $(\epsilon_{\text{DC}}, f_\alpha, \tau_\alpha)$-plane.

Figure 1. Left Panel: Joint constraints on $\epsilon_{\text{DC}}$ and $f_\alpha, \tau_\alpha$. The likelihood contours at 64%, 26% and 10% of the peak likelihood are shown at $z = 5.7$ as dashed contours with those at $z = 6.5$ overlaid as solid contours. Although the likelihood peaks at different values for $\epsilon_{\text{DC}}$ and $f_\alpha, \tau_\alpha$ at $z = 5.7$ and $z = 6.5$, the contours at both redshifts fill the same region of the $(\epsilon_{\text{DC}}, f_\alpha, \tau_\alpha)$-plane. A strong degeneracy exists between $\epsilon_{\text{DC}}$ and $f_\alpha, \tau_\alpha$ (see text). Right Panel: Slices through the likelihood surface at $\epsilon_{\text{DC}} = 0.06$ and $\epsilon_{\text{DC}} = 0.06$ are shown at $z = 5.7$ (black solid lines) and at $z = 6.5$ (red dotted lines), normalised to a peak of unity. For a given $\epsilon_{\text{DC}}$, $f_\alpha, \tau_\alpha$ peaks at very similar values at both redshifts. Assuming that $f_\alpha$ remains constant between $z = 5.7$ and $z = 6.5$, this suggests that the IGM transmission evolves only weakly between $z = 5.7$ and $z = 6.5$.

3 The data points represent a cumulative number of galaxies with Lyα luminosities exceeding $L_{\text{Ly}\alpha}$. The data points are therefore not completely independent. However, the number of galaxies more than doubles between most bins, and the errorbars do not overlap. This indicates that although cumulative, the points are close to independent.

4 Reducing $\epsilon_{\text{DC}}$ and $f_\alpha, \tau_\alpha$ by the same factor yields the same Lyα luminosity. However, because the galaxies are visible for a shorter time, this still results in the prediction of fewer objects. This causes the deviation from a 45-degree degeneracy-line in the $(\epsilon_{\text{DC}}, f_\alpha, \tau_\alpha)$-plane: changing $\epsilon_{\text{DC}}$ by 1 order of magnitude...
In Figure 2 we show the best fit models at $z = 6.5$ and $z = 5.7$. Clearly, the models provide an adequate fit to the data. We also show the model $z = 7.0$ LF (black dot-dashed line), under the assumption that only the halo mass function evolved between $z = 6.5$ and $z = 7.0$. The triangle represents the density implied by the $z = 7.0$ galaxy discovered by Iye et al. (2006). This density is consistent with the model LF at the $1 - \sigma$ level, suggesting that no drastic change in the IGM transmission is required between $z = 6.5$ and $z = 7.0$.

At $z = 5.7$ the duty cycle was found to lie in the range $\epsilon_{DC} = [0.03, 1.0]$, while at $z = 6.5$ this range was $\epsilon_{DC} = [0.1, 1]$. The likelihood in $\epsilon_{DC}$ therefore extends over more than 1 dex in each case. As a result, the a-posteriori probability for $\epsilon_{DC}$ is quite sensitive to the choice of a prior probability. Thus the data do not really constrain the duty cycle. Therefore, in the right panel of Figure 1 we show slices through the likelihood surface at $\epsilon_{DC} = 0.06$ and at $\epsilon_{DC} = 0.6$ respectively, normalised to a peak of unity. The distribution of $f_\alpha T_\alpha$ at $z = 5.7$ and $z = 6.5$ are shown as the black solid and red dotted lines. For fixed $\epsilon_{DC}$, the most likely values of $f_\alpha T_\alpha$ are common at both redshifts. Assuming that $f_\alpha$ does not evolve between $z = 5.7$ and $z = 6.5$, it therefore follows that the IGM transmission need not evolve significantly between $z = 5.7$ and $z = 6.5$ in order to explain the evolution of the LF. Thus the evolution in the observed LF may be attributed to the mass function of dark matter halos alone. This is explored in more detail in § 4.2.

Note that the best fit values for $f_\alpha T_\alpha = [0.01 - 0.05]$ meet our prior expectations. For $f_\alpha = 0.1$, we find $T_\alpha = 0.1 - 0.5$, which corresponds to the range of transmissions found in Dijkstra et al. (2007). In our best-fit models, the mass range of Ly$\alpha$ emitters is $M_{tot} \sim 4 - 42 \times 10^{10} M_\odot$ at $z = 5.7$ and $M_{tot} \sim 6 - 32 \times 10^{10} M_\odot$ at $z = 6.5$. This is compensated for by changing $f_\alpha T_\alpha$ only by half an order of magnitude.

4.1 Evolution of IGM Transmission

In this section we investigate the evolution of the IGM transmission, $T_\alpha$, in more detail. We found that the observed LFs can be described by models over a large range in duty cycle $\epsilon_{DC}$. Here, we fix the duty cycle and $f_\alpha$ to be common between $z = 5.7$ and $z = 6.5$, and vary the parameters $f_\alpha T_\alpha$ and $R \equiv T_\alpha / T_\odot$, where $T_\alpha$ and $T_\odot$ are the IGM transmission at $z = 5.7$ and $z = 6.5$, respectively. We compute model LFs on a grid in the $(R, f_\alpha T_\alpha)$-plane and simultaneously fit to the observed LFs at $z = 5.7$ and $z = 6.5$.

The results of this calculation are shown in Figure 3. Here, likelihood contours at 64%, 26% and 10% of the peak likelihood in the $(T_\alpha / T_\odot, f_\alpha T_\alpha)$-plane, for three different duty cycles $\epsilon_{DC}$. The models that provide the best fit to the observed LFs have $T_\alpha / T_\odot \sim 0.8 - 1.5$. Therefore, the best fit-models do not favour a large change in the opacity of the IGM to Ly$\alpha$ photons emitted by galaxies.

4.2 Constraints on Transmission from the Ly$\alpha$ and UV-Luminosity Functions.

In the previous section we derived constraints on the ratio $T_\alpha / T_\odot$ using a simple model for the Ly$\alpha$ LF in which the star formation rate in a galaxy increases in proportion to $M_{tot}$, the total mass of its host dark matter halo. We showed that the observed evolution in the Ly$\alpha$ LF can be attributed to the evolution of the mass function of dark matter halos. As evidenced by Figure 3, our exact constraints are somewhat dependent on the unknown model parameter $\epsilon_{DC}$. The goal of this section is to obtain constraints on $T_\alpha$ that are independent of any of our model parameters, and more generally, to obtain constraints that are independent of the model that underlies the Ly$\alpha$ LF.

Kashikawa et al. (2006) found that the rest-frame UV-LF of LAEs does not evolve between $z = 5.7$ and $z = 6.5$. This is consistent with the model LF.
This appears to contradict the conclusion that the evolution of dark matter halos (possibly in combination with cosmic variance) caused the observed evolution of the Lyα LF. Indeed, if the rest-frame UV-LF of LAEs is identical at \( z = 5.7 \) and \( z = 6.5 \), then the entire difference between the Lyα LFs at \( z = 5.7 \) and \( z = 6.5 \) must be due to a change in either \( T_\alpha \) or in the ratio \( L_{\alpha}/L_{\text{UV}} \) (where \( L_{\text{UV}} \) is rest-frame UV luminosity of a galaxy). In other words, a lower IGM transmission (or \( L_{\alpha}/L_{\text{UV}} \) ratio) at \( z = 6.5 \) would shift the Lyα luminosity function to the left relative to the \( z = 5.7 \) Lyα LF. Assuming for the moment that \( L_{\alpha}/L_{\text{UV}} \) remains constant, we quantify the ratio \( R \equiv T_{\alpha,6.5}/T_{\alpha,5.7} \) that is favored by this constraint. While the analysis could be done for individual galaxies, we consider the sample as a whole, by taking the model parameters \((f_{\alpha}, \epsilon_{\text{PC}})\) of our best-fit \( z = 5.7 \) model. Then we obtain \( z = 6.5 \) Lyα LFs for a range of \( T_{\alpha,6.5} \) by scaling the luminosities in the \( z = 5.7 \) model by a factor of \( T_{\alpha,6.5}/T_{\alpha,5.7} \). In Figure 4 we plot the likelihood, \( \mathcal{L}[P] = \exp[-0.5x^2] \), as function of the ratio \( T_{\alpha,6.5}/T_{\alpha,5.7} \). If the UV-LF remained constant between \( z = 5.7 \) and \( z = 6.5 \), then we find \( R = 1.4^{+0.3}_{-0.1} \) (95% CL). The preferred ratio decreases if the UV-LF at \( z = 6.5 \) lies below that at \( z = 5.7 \). Existing data is inconclusive regarding the precise evolution of the UV-LF between \( z = 5.7 \) and \( z = 6.5 \): from the size of the error-bars in Figure 7 of [Kashikawa et al. (2006)], we find that the best-fit \( z = 6.5 \) UV-LF to lie higher by a factor of \( 0.7 \pm 0.2 \) (95%) than at \( z = 5.7 \) if all data points brighter than \( M_{\text{UV}} = -20 \) are used, while it lies higher by a factor of \( 1.2 \pm 0.4 \) (95%) if the two data points at \( M_{\text{UV}} \sim -20.2 \) are ignored. Figure 4 shows the the likelihood of the ratio \( T_{\alpha,6.5}/T_{\alpha,5.7} \) assuming that the \( z = 6.5 \) LF lies higher by a factor of 0.7 [1.2] as the dotted [dashed] line. Assuming for simplicity that the ratio of \( z = 6.5 \) and \( z = 5.7 \) UV-LFs has a flat likelihood distribution between 0.7 and 1.2, then it follows from Figure 4 that 1.1 < \( R < 1.8 \) (\( \sim 95\% \) CL).

We quantify in more detail below how this compares to the evolution of the transmission in a fully (§ 4.3) and partially (§ 4.4) reionised universe.

The relative normalisations of the UV & Lyα LFs may evolve for reasons other than transmission. Either (1) \( L_{\text{UV}} \) increases with reionization, or (2) \( L_{\alpha} \) decreases with reionization. (1) could be caused by decreasing dust abundance towards higher redshift. However, the observed Lyα LF requires that Lyα is affected less by this possible evolution of the dust content, which in turn requires fine tuning of how the dust is distributed. (2) could be caused by an increasing escape fraction of ionising photons with reionization as \( L_{\alpha} \propto (1 - f_{\text{esc}}) \). Recently, [Inoue et al. (2006)] found that \( f_{\text{esc}} \) is roughly consistent with the value \( f_{\text{esc}} \sim 0.1 \) at \( 4 \leq z \leq 6 \). In order for \( L_{\alpha} \) to increase by a factor of \( \geq 1.1 \) between \( z = 6.5 \) and \( z = 5.7 \) would require \( f_{\text{esc}} \geq 0.2 \) at \( z = 6.5 \).

### 4.3 Cosmic Expansion and the Evolution of \( T_\alpha \)

Following the analysis presented in [Dijkstra et al. (2007)], we calculate the IGM transmission \( (T_\alpha) \) at \( z = 5.7 \) and \( z = 6.5 \), and the expected value of the ratio of transmission \( R \equiv T_{\alpha,5.7}/T_{\alpha,6.5} \). We calculate \( T_\alpha \) for a model in which \( M_{\text{tot}} = 10^{11} \, M_\odot \) (the centroid of our best-fit mass range for the host halos of the LAEs § 4.1, and \( M_\odot = 10 \, M_\odot \)/yr. The Lyα line before scattering in the IGM is assumed to be Gaussian with a standard deviation of \( v_{\text{esc}} \). The density and velocity profiles of gas in the IGM are described in [Dijkstra et al. (2007)]. Note that the precise value of \( T_\alpha \) differs with quantities such as \( M_{\text{tot}} \), \( M_\odot \), and other parameters such as the assumed width of the Lyα line, and the peculiar velocity of the galaxies relative to the surrounding IGM [Dijkstra et al. 2007]. However, as long as these quantities do not vary significantly between the samples at \( z = 5.7 \) and \( z = 6.5 \), these uncertainties should not strongly affect the calculation of the ratio \( R \).

We consider two cases: in case I the photoionisation rate due to the externally generated, ionising background is set to \( 10^{-13} \, \text{s}^{-1} \) as derived from quasar absorption spectra (e.g. [Fan et al. 2006]). In case II clustering of nearby, undetected, sources boosts the photoionisation rate considerably. We include the effects of clustering using the prescription in [Dijkstra et al. (2007)]. Clustering of sources and the corresponding boost in the local ionising background occurs naturally in hierarchical models [Wyithe & Loeb 2003]. In both cases, the only difference between models at \( z = 5.7 \) and \( z = 6.5 \) is the mean density of baryons in the universe. Figure 5 shows the observed Lyα lines after processing through the IGM. The horizontal axis shows the normalized frequency \( x \equiv (\nu - \nu_\alpha)/\Delta\nu_D \). Note that \( x = 0 \) corresponds to the true line center. The flux density on the horizontal axis is in arbitrary units. Here, case I (no boost) is shown in the left panel and case II (with boost) is shown in the right panel. The labels denote the values of \( R \).

Figure 5 shows that the infalling gas erases part of the Lyα line redward of the Lyα resonance, and produces a

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Figure 4. The likelihood distribution of the ratio \( T_{\alpha,6.5}/T_{\alpha,5.7} \) derived from the Lyα + rest-frame UV luminosity function. Three curves are shown: the solid line shows the likelyhood under the assumption that the UV-LFs of LAEs are identical at \( z = 6.5 \) and \( z = 5.7 \). The dotted/dashed line shows the likelihood under the assumption that the UV-LFs of LAEs at \( z = 5.7 \) lies higher by a factor of 0.7 and 1.2, respectively. The grey thick line at \( R < 1.3 \) shows the range of ratios that can be expected if the Universe remained fully reionised between \( z = 6.5 \) and \( z = 5.7 \) (§ 4.3).
Figure 5. Lyα spectra of LAEs at \( z = 5.7 \) (black line) and \( z = 5.7 \) (grey line) after processing through a fully reionised IGM. In the left/right panel the local ionising background is not/is enhanced due to the clustering of nearby undetected sources. The figure shows that \( R \equiv T_{\alpha,57}/T_{\alpha,65} \) may be as large as \( R = 1.3 \) without invoking any drastic change in the ionisation state of the IGM.

sharp cut-off in the Lyα line at \( x > -10 \) (see Dijkstra et al. 2007 for a more detailed discussion of this). For case I, \( R = 1.03 \), which is outside the acceptable range found in § 4.2. For case II however, the boost in the ionising background reduces the neutral fraction in the IGM, which allows a small fraction of Lyα to ‘leak’ through the IGM. In this case the total fraction of Lyα that is transmitted depends quite strongly on the mean density of hydrogen, which results in \( R = 1.3 \), well within the acceptable range for \( R \) and less than 20 away from the best-fit model if the UV-LF of LAEs were identical at \( z = 5.7 \) and \( z = 6.5 \).

4.4 Constraints from \( R \equiv T_{\alpha,57}/T_{\alpha,65} < 1.8 \)

In the previous section we found that the ratio of transmissions \( R = T_{\alpha,57}/T_{\alpha,65} \) expected for a fully reionised IGM out to \( z > 6.5 \) can be as large as \( R = 1.3 \). Following the analysis presented in Dijkstra et al. (2007), we calculate the expected value of \( R \) for cases in which galaxies at \( z = 6.5 \) are embedded in bubbles of reionised gas of radius \( R_{\text{HII}} \), within an otherwise neutral IGM. Prior to overlap, HII bubbles are expected to be generated by clusters of ionising sources. Their sizes therefore greatly exceed that of HII regions of individual galaxies (Furlanetto et al. 2004a,b; Wyithe & Loeb 2004b; Zahn et al. 2007). The associated value of \( R \) is shown in Figure 6 as a function of bubble radius for cases in which the local ionising background is (not boosted) by nearby undetected sources as the dashed (solid) line.

Figure 6 shows that \( R \) decreases with bubble size (\( R_{\text{HII}} \)), as the damping wing absorption becomes less important. The minimum bubble radius shown corresponds to the case of an isolated galaxy in its own HII region. For large bubble sizes the ratio levels off for the boosted (not boosted) case at \( R = 1.3 \) (\( R = 1.03 \)). These are the values quoted in § 4.3 in reference to an ionised IGM at higher density. The light grey area shows the range \( R \in [1.1 \text{--} 1.8] \) that was preferred by the combination of the UV and Lyα LF (§ 4.2). According to Figure 6 the constraint \( R < 1.8 \) translates to a minimum bubble radius of \( R_{\text{HII}} \geq 2 \) pMpc, which translates to \( R_{\text{HII}} \geq 15 \) cMpc. In the model of Furlanetto et al. (2006) the characteristic HII-bubble size at a given epoch is related to the globally averaged ionised fraction of the universe by volume, \( x_{1,V} \) at that epoch. If we assume that the LAEs at \( z = 6.5 \) reside in HII-bubbles that are of characteristic size at \( z = 6.5 \), then the constraint \( R_{\text{HII}} \geq 15 \) cMpc translates to \( x_{1,V} \geq 0.8 \). However, the actual lower limit on \( x_{1,V} \) is weaker: if the Universe were truly more than 80% ionised by volume at \( z = 6.5 \), then the neutral IGM surrounding the HII bubble would be filled with other ionised bubbles, which would reduce the damping wing optical depth of the IGM, which would enhance \( T_{\alpha,65} \) and thus reduce \( R \). If the damping wing optical depth is reduced by a factor of 2 (which is roughly the case when the universe is half ionised by volume), then we find...
our lower limit on bubble size to be $R_{\text{HI}} \geq 6 - 10$ cMpc, which translates to $x_{\text{I},V} \geq 0.5 - 0.6$. Note that this lower limit on $x_{\text{I},V}$ would also be obtained directly from the constraint $R_{\text{HI}} \geq 15$ cMpc, when the impact of feedback from clustered sources is included, which modifies the relation between $R_{\text{HI}}$ and $x_{\text{I},V}$ (Kramer et al. 2006). In summary, the upper limit on $R$ suggests that a more reasonable lower limit on the ionised fraction of the Universe is $x_{\text{I},V} \geq 0.5$.

5 DISCUSSION & CONCLUSIONS

Recent observations have shown that the observed number counts of Lyα emitters evolve significantly between $z = 5.7$ and $z = 6.5$ (Kashikawa et al. 2006). It has been suggested that this evolution could be due to a significant change in the ionisation state of the IGM during this short time interval. In this paper we have investigated the constraints that may be placed on the evolution of the IGM transmission using the observed UV and Lyα LFs at $z = 5.7$ and $z = 6.5$.

We used a simple prescription to relate the Lyα luminosity of a galaxy to the mass of its host dark matter $M_{\text{tot}}$ and found that such a model can reproduce the data quite well. Using this model, we have shown that the observed Lyα LFs at $z = 5.7$ and $z = 6.5$ are best described by a model in which the IGM transmission evolves only weakly between these two redshifts. In fact, it is possible to attribute the observed evolution in the Lyα LF entirely to the evolution in the mass function of dark matter halos. The presence of cosmic variance in the observations strengthens this conclusion.

However, the observed rest-frame UV-LF of Lyα emitters appears not evolve between $z = 5.7$ and $z = 6.5$. Accounting for the co-evolution implies that the observed evolution of the Lyα LF may indeed be due to the evolution of the IGM transmission between $z = 6.5$ and $z = 5.7$. We find in this case that the ratio of transmissions is $1.1 < R \equiv T_{\alpha,57}/T_{\alpha,65} < 1.8$ (≈ 95% confidence levels). This result is insensitive to the underlying model of the Lyα LF (as well as cosmic variance). However, we find that the ratio of transmissions expected for a fully reionised IGM out to $z \geq 6.5$ can be as large as $R = 1.3$. Thus as with consideration of the Lyα LF's alone, the observed evolution is consistent with no change in the ionisation state of the IGM. The existing LFs therefore do not provide evidence for overlap between $z = 5.7$ and $z = 6.5$. Furthermore, the upper limit $R \equiv T_{\alpha,57}/T_{\alpha,65} < 1.8$ implies that the Universe at $z = 6.5$ was more than half ionised by volume, i.e. $x_{\text{I},V} > 0.5$.

The present paper is based on observed LFs that were derived from spectroscopic observations of 17 $z = 6.5$ and 28 $z = 5.7$ Lyα emitters. A larger sample of Lyα emitters at both redshifts will allow more stringent constraints to be placed on simple models such as those presented here. In particular, the existing LF covers 1 dex in luminosity only. A larger range in luminosities will be useful for (i) breaking model degeneracies and determining the duty cycle and (ii) determining the evolution of the IGM transmission $T_{\alpha}$ to greater accuracy, especially when Lyα LFs are used in combination with the UV-LF of Lyα emitters. This will provide constraints on the epoch of reionization which are independent of those derived from quasar absorption studies. An improved determination of the observed Lyα LF will also allow constraints to be placed on more sophisticated models, that account for the impact of the interstellar medium on the Lyα emission from galaxies (as in Haiman & Spaans 1999), include galaxy clustering and account for scatter in quantities such as $f_{\alpha}, T_{\alpha}, \epsilon_{\text{PC}}$ etc. These issues will be addressed in future work.

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