Mass-to-light ratio of Lyα emitters: implications of Lyα surveys at redshifts z = 5.7, 6.5, 7 and 8.8

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ABSTRACT

Using a simple method to interpret the luminosity function of Lyα emitters, we explore properties of Lyα emitters from 5.7 ≤ z ≤ 8.8 with various assumptions about metallicity and stellar mass spectra. We constrain a mass-to-‘observed light’ ratio, M_h/L_band, where M_h refers to the total mass of the host halo and L_band refers to the observed luminosity of the source. For narrow-band surveys, L_band is simply related to the intrinsic Lyα luminosity with a survival fraction of Lyα photons, α_esc. The mass-to-‘bolometric light’, M_h/L_bol, can also be deduced, once the metallicity and stellar mass spectrum are given. The inferred M_h/L_bol is more sensitive to metallicity than to the mass spectrum. We find the following constraints on a mass-to-light ratio of Lyα emitters from 5.7 ≤ z ≤ 7: (M_h/L_bol)(α_esc e^{1/γ})^{-1} = 21–38, 14–26 and 9–17 for Z = 0, 1/50 and 1 Z⊙, respectively, where e is the ‘duty cycle’ of Lyα emitters and γ ~ 2 is a local slope of the cumulative luminosity function, N(L) ∝ L^{−γ}, to which the current data are sensitive. Only weak lower limits are obtained for z = 8.8. Therefore, Lyα emitters are consistent with either starburst galaxies (M_h/L_bol ~ 0.1–1) with a smaller Lyα survival fraction, α_esc e^{1/γ} ~ 0.01–0.05, or normal populations (M_h/L_bol ~ 10) if a good fraction of Lyα photons survived, α_esc e^{1/γ} ~ 0.5–1. We find no evidence for the end of reionization in the luminosity functions of Lyα emitters discovered in the current Lyα surveys, including recent discovery of one Lyα emitter at z = 7. The data are consistent with no evolution of intrinsic properties of Lyα emitters or neutral fraction in the intergalactic medium up to z = 7. No detection of sources at z = 8.8 does not yield a significant constraint yet. We also show that the lack of detection at z = 8.8 does not rule out the high-z galaxies being the origin of the excess near-infrared background.

Key words: galaxies: high-redshift – cosmology: observations – cosmology: theory – early Universe – infrared: galaxies.

1 INTRODUCTION

What was the Universe like at high redshifts? We are currently entering a time where we can begin to observe this early time in the Universe’s life by looking for galaxies at redshifts above six.

There are several indications that stars, and hence galaxies, existed at this early time. We know that the Universe was reionized early from observations such as the polarized light of the cosmic microwave background (Zaldarriaga 1997; Kaplinghat et al. 2003; Kogut et al. 2003; Page et al. 2007; Spergel et al. 2007), the Gunn–Peterson test towards quasars (e.g. Gunn & Peterson 1965; Fan et al. 2000; Becker et al. 2001; Fan et al. 2001, 2002, 2004; Oh & Furlanetto 2005; Goto 2006) and a gamma-ray burst (Totani et al. 2006) and the temperature of the intergalactic medium (Hui & Haiman 2003).

In order to produce large-scale reionization, an efficient and plentiful source of ultraviolet photons was needed. The first few generations of stars are very likely candidates, producing ultraviolet photons efficiently. The Lyα forest shows that the Universe was polluted with metals as early as z ~ 6 (Songaila 2001; Pettini et al. 2003; Ryan-Weber, Pettini & Madau 2006; Simcoe 2006), indicating even earlier star formation, and thus providing further support of early stars. In addition, a portion of the near-infrared background could be the redshifted light from the first stars, and may provide information about them (Santos, Bromm & Kamionkowski 2002; Salvaterra & Ferrara 2003; Cooray & Yoshida 2004; Kashlinsky et al. 2005; Madau & Silk 2005; Cen & Haiman 2003; Fernandez & Komatsu 2006; Kashlinsky et al. 2007).

It is therefore very likely that there is significant star formation above z > 6. With the introduction of new, more powerful telescopes and deep field searches, an interesting question arises: do these first stars form galaxies that are bright enough to be seen today? Several deep field Lyα searches have been performed with
2 A SIMPLE MODEL OF GALAXY COUNTS

2.1 Justification for a simplified approach

The simplest way to predict the cumulative luminosity function of galaxies is to count the number of haloes available in the Universe above a certain mass,

\[ N(>L) = V(z) \int_{M(h)}^\infty \frac{dn}{dM_h} dM_h, \]

where \( V(z) \) is the survey volume, \( \frac{dn}{dM_h} \) is the comoving number density of haloes per unit mass range and \( M_h \) is the total mass of a halo.

The cumulative number density of haloes, \( \int_{M(h)}^\infty \frac{dn}{dM_h} dM_h \), is shown in the bottom panel of Fig. 1. In order to calculate the cumulative luminosity function, one may simply ‘stretch’ the horizontal axis of this figure by dividing \( M_h \) by a suitable factor that converts the mass to luminosity: a mass-to-light ratio, \( M_h/L \).

This model is admittedly oversimplified, and is indeed simpler than what is already available in the literature. For example, one can stretch not only the horizontal axis (i.e. mass), but also the vertical axis of the cumulative mass function as \( \int \frac{dn}{dM_h} dM_h \rightarrow \epsilon \int \frac{dn}{dM_h} dM_h \), where \( \epsilon \) is often called a ‘duty cycle’ (e.g. Haiman, Spaans & Quataert 2000).

The vertical stretch would be required when the average lifetime of Ly\( \alpha \) emitting galaxies, \( \tau_{Ly\alpha} \), is shorter than the age of the Universe, in which case the number count should be given by the time derivative of the mass function, \( \int \frac{dn}{dM_h} \epsilon \frac{d\tau_{Ly\alpha}}{dM_h} \). The vertical stretch parameter is thus given approximately by \( \epsilon \approx \tau_{Ly\alpha}/(\text{time}) \).

Since the statistical power of the current data is not yet strong enough to constrain both the horizontal and the vertical stretch parameters simultaneously, these parameters are strongly degenerate (Dijkstra, Wyithe & Haiman 2007b; Stark, Loeb & Ellis 2007). They are completely degenerate when \( N(>L) \) follows a single power law, \( N(>L) \propto L^{-\gamma} \). The degeneracy line is given by \( (M_h/L)\epsilon = \text{constant} \); thus, the inferred \( M_h/L \) and \( \epsilon \) are positively correlated: the smaller the \( \epsilon \) is the smaller the inferred \( M_h/L \) becomes.

In order to lift this degeneracy, therefore, it is essential to detect the deviation of \( N(>L) \) from a power law. Since the cumulative mass function in 5.7 \( \lesssim z \lesssim 8.8 \) begins to decline exponentially with mass at a few times \( 10^{11} M_\odot \) at \( z \approx 6 \) to \( 10^{10} M_\odot \) at \( z \approx 9 \) (see Fig. 1), an accurate determination of the bright end of the luminosity function at \( L_{Ly\alpha} \gtrsim 10^{42} \text{erg s}^{-1} \times (100 L_{Ly\alpha}/M_h) \) at \( z \sim 9 \) to \( 10^{40} \text{erg s}^{-1} \times (100 L_{Ly\alpha}/M_h) \) at \( z \sim 6 \) would be required to lift the degeneracy. (Note that \( M_h/L \) is always quoted in units of \( M_\odot L_\odot^{-1} \), where \( L_\odot = 3.8 \times 10^{33} \text{erg s}^{-1} \).) The bright end of the luminosity function is not constrained very well by the existing surveys (see Fig. 2). One would need a larger survey area for a better determination of the bright end of the luminosity function. (See Section 4.1 for further discussion on constraining the bright end of the luminosity function.) We have chosen to work with \( \epsilon = 1 \), which is allowed by the existing data (Dijkstra et al. 2007b; Stark et al. 2007). As we show in this paper, this assumption does provide reasonable and useful results. We then use the degeneracy line, \( (M_h/L)\epsilon^{-1/\gamma} = \text{constant} \), to incorporate the effect of \( \epsilon \) into the inferred constraints on properties of \( Ly\alpha \) emitters.

A further improvement to the model can be made by taking into account the fact that a relation between the luminosity and the halo mass is not unique, but has some dispersion. One may include this by using a conditional probability of luminosity given the halo mass, \( P(L|M_h) \), as \( N(>L) = V(z) \int dM_h P(L|M_h) dM_h \). The cumulative luminosity function given by, for example, a log-normal distribution (Cooray & Milosavljevic 2005). Once again, the current data cannot constrain the extra parameters characterizing \( P(L|M_h) \) except for its first-order moment, a mass-to-luminosity ratio. In our simplified approach, we take it to be a delta function, \( P(L|M_h) = \delta[L-M_h/(M_h/L)] \), which gives equation (1).

![Figure 1](https://academic.oup.com/mnras/article-abstract/384/4/1363/958283/1363–1376)
Figure 2. The observed luminosity function of Lyα emitters constrains their mass-to-‘observed light’ ratio. Each panel shows the cumulative number of sources detected in each field above a certain flux density, $N(>F)$. (The flux density limits of each survey are indicated by the vertical lines with right arrows.) The bottom and top axes show the measured flux density and luminosity (in erg s$^{-1}$), respectively, while the left- and right-hand sides show the number of sources per field and per comoving Mpc$^3$, respectively. The mass-to-‘observed light’ ratio, $M_h/L_{\text{band}}$, is fit to each of the luminosity functions derived from various narrow-band surveys. Here, $L_{\text{band}}$ refers to the light that falls within the band of instruments, which is mostly the Lyα line. Curves in each panel show the predictions with various $M_h/L_{\text{band}}$. Upper left-hand panel: the Subaru field at $z = 5.7$ (Shimasaku et al. 2006). The stars, triangles and diamonds show their Schechter-fit to the luminosity function with $\alpha = -2$, $-1.5$ and $-1$, respectively. The scatter between symbols shows uncertainty, and they diverge mostly below the flux density limit, as expected. The solid circles are the data, with the error bars showing Poisson error. Upper right-hand panel: the LALA field at $z = 6.55$ (Rhoads et al. 2004). One Lyα emitter was found, and the horizontal line shows $N(>F) = 1$ per field. Middle left-hand panel: the Subaru field at $z = 6.56$ (Taniguchi et al. 2005; Kashikawa et al. 2006). The meaning of symbols is the same as in the upper left-hand panel. Data are from both the photometric and the spectroscopic samples. The circles show data corrected for detection completeness. Middle right-hand panel: the Subaru field at $z = 7.025$ (Iye et al. 2006). One Lyα emitter was found. Bottom left-hand panel: the ZEN field at $z = 8.76$ (Willis & Courbin 2005; Willis et al. 2006). No sources were found, and the horizontal line with lower arrows shows $N(>F) < 1$ per field. Bottom right-hand panel: The ISAAC ext field at $z = 8.76$ (Cuby et al. 2007). No sources were found.
In this paper, we will use the Sheth–Tormen formula for $dn/dM$ (Sheth, Mo & Tormen 2001; Sheth & Tormen 2002). Since the Press–Schechter mass function (Press & Schechter 1974) tends to underestimate the number of haloes in the high-mass range, the mass-to-light ratio inferred from the Press–Schechter mass function would be smaller than that from the Sheth–Tormen formula. We have found that the mass-to-light inferred from the Press–Schechter mass function is smaller by a factor of 2.

The volume, $V(z)$, is found by multiplying the comoving volume element, $dV/dz = \Omega$, by the depth of the survey (found by integrating over redshift) and the survey area on the sky. For narrow-band surveys, the redshift integral can be approximated as $\Delta z$. The comoving volume element is given by

$$\frac{dV}{dz\Omega} = \frac{cH(z)}{1+z} \left[ \frac{1}{H(z)(1+z)} \right],$$

where $c$ is the proper luminosity distance.

### 2.2 Basic formalism

From equation (1), we can derive the number of galaxies observed above a certain flux density as

$$\int_{F_{\text{lim}}}^{\infty} \frac{d^2N}{dF\Omega} dF = \int dz \frac{dV}{dz\Omega} \int_{F_{\text{lim}}}^{\infty} \frac{dn}{dM} \frac{dM}{dF} \theta[M_h - M_{\text{min}}(z)] dF \approx \Delta z \frac{dV}{dz\Omega} \int_{F_{\text{lim}}}^{\infty} \frac{dn}{dM} \frac{dM}{dF} \theta[M_h - M_{\text{min}}(z)] dF,$$

and $M_h$ is the halo mass.

Not all dark matter haloes will be forming stars – only haloes with a mass above some critical minimum mass ($M_{\text{min}}$). This is represented by the function $\theta[M_h - M_{\text{min}}(z)]$, which is zero if the halo mass is smaller than $M_{\text{min}}$ and unity if it is larger than or equal to $M_{\text{min}}$. The minimum mass is only theoretically known, and we use the virial mass of a 10 000 K halo, $M_{\text{min}} = 0.94 \times 10^8 M_\odot (1+z)^{1/3}$. However, given the current sensitivity of telescopes, it is unlikely that a halo of mass $M_{\text{min}}$ will be bright enough to be seen, unless the mass-to-light ratio of galaxies is unusually small. Therefore, $M_{\text{min}}$ is irrelevant to our analysis presented in this paper and our conclusion is independent of the actual value of $M_{\text{min}}$.

In deriving equation (3), we have made an assumption that each dark matter halo above $M_{\text{min}}$ hosts one galaxy. This is a valid assumption at high redshifts, as massive haloes such as groups ($M \geq 10^{13} M_\odot$) and clusters ($M \geq 10^{14} M_\odot$) of galaxies hosting multiple emitters are extremely rare (see Fig. 1). If we were to assume a field size equal to the largest survey area discussed in this paper (that of the Large Area Lyman Alpha (LALA) survey, 1296 arcmin$^2$), and the widest redshift range (that of the Subaru survey at $z \sim 7$), the number of haloes above a mass of $10^{13} M_\odot$ can be found by using equation (1). At a redshift of one, there would be 32 haloes larger than this mass in the field. At higher redshifts ({$z = 3, 5$ and 7}), there would be less than one such massive halo in the field (0.98, $1 \times 10^{-3}$ and $7.7 \times 10^{-3}$, respectively.) Thus at high redshifts, it is safe to assume that there are no groups or clusters observed. (Larger surveys Ouchi et al. 2005 have observed protoclusters). This property makes it possible to model the luminosity function of high-$z$ galaxies without complications arising from galaxy formation processes. Some observations (i.e. Ouchi et al. 2004) show that some dark matter haloes host more than one Ly$\alpha$ emitter. However, since galaxy occupation number at high redshifts is not well known, we will just assume one galaxy per halo.

The most important uncertainty in our model is that not all galaxies are Ly$\alpha$ emitters. Some galaxies do not produce as many Ly$\alpha$ photons as the others do because of dust extinction in galaxies themselves and scattering in the intergalactic medium (IGM). Therefore, we could have assumed that there is less than one Ly$\alpha$ emitter per halo; however, this effect can be modelled effectively by introducing a Ly$\alpha$ survival fraction, $\alpha_{\text{surv}}$. This parameter quantifies the fraction of Ly$\alpha$ photons that escaped from a halo and the IGM. Therefore, as $\alpha_{\text{surv}}$ increases, a galaxy is seen as more luminous intrinsically.

In summary, we model the galaxy number counts by placing one galaxy per halo with only a fraction of photons escaping from galaxies and the IGM.

### 2.3 Mass-to-‘observed light’ ratio

Our formulation is now reliant on how we relate the flux density of a galaxy to its mass.

The flux density of galaxies depends on two things: the luminosity distance to galaxies and a mass-to-‘observed light’ ratio, which will relate the total mass of the halo (including dark matter) to the luminosity that is actually observed. The flux density of a galaxy observed by a certain instrument is found by

$$F = \frac{L_{\text{band}}/M_h}{4\pi d_L^2(z)\Delta V_{\text{obs}}} M_h,$$

where $\Delta V_{\text{obs}}$ is the bandwidth of the instrument (which we have assumed to have an ideal rectangular bandpass) and

$$L_{\text{band}} = \int_{v_{\text{lim}}(1+z)}^{v_{\text{obs}}(1+z)} dv L_\nu,$$

is the observed luminosity within a certain bandwidth of the instrument, $L_\nu$ is the rest-frame luminosity per unit rest-frame frequency, and $v_{\text{lim}}$ and $v_{\text{obs}}$ are the frequency limits of the survey.

We assume that the mass-to-light ratio is independent of mass, $dM_\nu/dF = M_h/F$. This approximation is well justified, as the current surveys are probing a limited mass range. Total and stellar masses are still unknown for Ly$\alpha$ emitters. Studies of the stellar masses using spectral energy distribution (SED) fitting have just begun (Mobasher et al. 2005; Nilsson et al. 2007). In the future, when the observations of Ly$\alpha$ emitters can cover a wide mass range, one may use a parametrized model, e.g. $L \propto M^\beta$, to improve fits. For the present purpose additional parameters are unnecessary.

Using equation (4), equation (3) can be rewritten with respect to $M_{\text{lim}}/L_{\text{band}}$ as

$$\int_{F_{\text{lim}}}^{\infty} \frac{d^2N}{dF\Omega} dF = 4\pi d_L^2(z) \frac{dV}{dz\Omega} \Delta z \Delta V_{\text{obs}} M_{\text{lim}} L_{\text{band}} \int_{F_{\text{lim}}}^{\infty} \frac{dn[M_h(F)]}{dF} dF \times \theta[M_h - M_{\text{min}}(z)].$$

To evaluate $dn/dM$ for a given $F$, we use equation (4) to convert $F$ to $M_h$. Once again, $M_{\text{lim}}/L_{\text{band}}$ is independent of $M_h$ and $M_h$ is almost always greater than $M_{\text{lim}}$, and thus almost always $\theta[M_h - M_{\text{min}}(z)] = 1$. The only unknown quantity in this equation is $M_{\text{lim}}/L_{\text{band}}$, where $\Delta V_{\text{obs}}, F_{\text{lim}}$ and $\Delta z$ are given by the survey properties. In other words, $M_{\text{lim}}/L_{\text{band}}$ is the parameter that should be measured from the observational data directly.
Three candidates were located down to a limiting magnitude of 24.3. A detection limit of 3 Jy was taken of the Bo"otes field. The limiting flux density was 700 nJ.

Candidates were found down to a limiting magnitude of 26.0 (at $\alpha = 6^{3}43$) were followed up by spectroscopy and 34 Ly-$\alpha$ emitters have been confirmed (Kashikawa et al. 2004). From these detections, they were able to fit a Schechter function, $\phi(L) dL = \phi^* (L/L^*)^{-\alpha} \exp(-L/L^*) dL/L^*$, with parameters given in Table 2.

The LALA survey searched for galaxies at a redshift of around $z = 5$. One effective method of locating high-redshift galaxies is to use narrow-band filters to detect Ly-$\alpha$ emission from a small range of redshifts. Ly-$\alpha$ emitters tend to have large equivalent widths (EWs), with their line intensities significantly higher than the continuum emission. In order to test that the galaxy is indeed a high-redshift galaxy, it must be undetected at optical wavelengths, and follow-up spectroscopy may be employed if possible. At times, when no continuum is visible, the asymmetric profile of the Ly-$\alpha$ line can be used to identify a Ly-$\alpha$ emitter.

Several telescopes are now powerful enough to attempt to locate galaxies at $z \gtrsim 6$. One effective method of locating high-redshift galaxies is to use narrow-band filters to detect Ly-$\alpha$ emission from a small range of redshifts. Ly-$\alpha$ emitters tend to have large equivalent widths (EWs), with their line intensities significantly higher than the continuum emission. In order to test that the galaxy is indeed a high-redshift galaxy, it must be undetected at optical wavelengths, and follow-up spectroscopy may be employed if possible. At times, when no continuum is visible, the asymmetric profile of the Ly-$\alpha$ line can be used to identify a Ly-$\alpha$ emitter.

A large number of such narrow-band Ly-$\alpha$ searches have been carried out on blank fields at $z = 5$ (Rhoads & Malhotra 2001; Ajiki et al. 2003; Ruotsala et al. 2003; Rhoads et al. 2003; Ajiki et al. 2004; Hu et al. 2004; Ouchi et al. 2005; Ajiki et al. 2006; Shimasaku et al. 2006; Murayama et al. 2007), $z = 6.5$ (Kodaira et al. 2003; Rhoads et al. 2004; Taniguchi et al. 2005; Kashikawa et al. 2006), $z = 7$ (Iye et al. 2006) and $z = 8.8$ (Willis & Courbin 2005; Willis et al. 2006; Cuby et al. 2007). Kurk et al. (2004) used an alternative technique, a slitless–grism spectroscopy survey, which has also yielded a successful detection of a Ly-$\alpha$ emitter at $z = 6.5$. Martin & Sawicki (2004) performed a multi-slit windows search at $z = 5.7$.

One of the potential advantages of narrow-band surveys is that they can be used to search for galaxies at a wide range of redshifts. For example, the LALA survey searched for galaxies at a redshift of around $z = 5$. One effective method of locating high-redshift galaxies is to use narrow-band filters to detect Ly-$\alpha$ emission from a small range of redshifts. Ly-$\alpha$ emitters tend to have large equivalent widths (EWs), with their line intensities significantly higher than the continuum emission. In order to test that the galaxy is indeed a high-redshift galaxy, it must be undetected at optical wavelengths, and follow-up spectroscopy may be employed if possible. At times, when no continuum is visible, the asymmetric profile of the Ly-$\alpha$ line can be used to identify a Ly-$\alpha$ emitter.

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Another survey using the Subaru telescope covered an area of 31 arcmin$^2$ down to a flux density of 302 nJ. There were two Ly-$\alpha$ emitter candidates down to a limiting magnitude of 24.9 (5$\sigma$) with a 2 arcsec aperture – one of which was confirmed spectroscopically as a Ly-$\alpha$ emitter at $z = 6.96$ (Iye et al. 2006). ZEN, which stands for $z$ equals nine, is a narrow-$J$-band mission using the ISAAC on the VLT. Its central redshift is 8.76 and it covers a field size of 4 arcmin$^2$ down to a limiting flux density of 302 nJ.

Table 1. Survey parameters taken from Shimasaku et al. (2006)$^a$, Rhoads et al. (2004)$^b$, Taniguchi et al. (2005)$^c$, Kashikawa et al. (2006)$^d$, Iye et al. (2006)$^e$, Willis & Courbin (2005)$^f$, Willis et al. (2006)$^g$ and Cuby et al. (2007)$^h$.

| Name of survey | Telescope | Central $\lambda$ (Å) | Bandwidth (Å) | Central $z$ | Redshift range | Area (arcmin$^2$) | Reference |
|----------------|-----------|-----------------------|---------------|-------------|----------------|----------------|-----------|
| Subaru Deep Field | Subaru | 8150 | 120 | 5.7 | 5.64–5.76 | 725 | a |
| LALA | Mayall | 9182 | 84 | 6.55 | 6.516–6.586 | 1296 | b |
| Subaru Deep Field | Subaru | 9196 | 132 | 6.56 | 6.508–6.617 | 876 | c, d |
| Subaru Deep Field | Subaru | 9755 | 200 | 7.025 | 6.94–7.11 | 876 | e |
| ZEN | VLT | 11900 | 89.5 | 8.76 | 8.725–8.798 | 4 | f, g |
| ISAAC ext | VLT | 11900 | 89.5 | 8.76 | 8.725–8.798 | 31 | h |

Table 2. Best-fitting Schechter parameters from Kashikawa et al. (2006). These data are plotted in Fig. 2.

| Redshift | $\alpha$ | $\log_{10}(L*/h_0^2$ erg s$^{-1}$) | $\log_{10}(\phi^*/h_0^3$ Mpc$^{-3}$) |
|----------|---------|---------------------------------|---------------------------------|
| 6.5      | -2.0    | 42.74                           | -3.14                           |
| -1.5     | 42.60   | -2.88                           |                                 |
| -1.0     | 42.48   | -2.74                           |                                 |
| 5.7      | -2.0    | 43.30                           | -3.96                           |
| -1.5     | 43.04   | -3.44                           |                                 |
| -1.0     | 42.84   | -3.14                           |                                 |

nJ. There were two Ly-$\alpha$ emitter candidates down to a limiting magnitude of 24.9 (5$\sigma$) with a 2 arcsec aperture – one of which was confirmed spectroscopically as a Ly-$\alpha$ emitter at $z = 6.96$ (Iye et al. 2006).

ZEN, which stands for $z$ equals nine, is a narrow-$J$-band mission using the ISAAC on the VLT. Its central redshift is 8.76 and it covers a field size of 4 arcmin$^2$ down to a limiting flux density of 302 nJ. They searched for galaxies in the Hubble Deep Field South that displayed an excess in the narrow band in comparison to the $J$-band $(J_z - NB \geq 0.3)$ and that were undetected in the optical. No galaxies were found down to a limiting magnitude of 25.2 (5$\sigma$) with a 0.7 aperture (Willis & Courbin 2005; Willis et al. 2006).

Cuby et al. (2007) did a follow-up narrow-band search, using the ISAAC at the VLT, with a larger field of view (hereafter referred to as the ISAAC ext). They imaged seven fields in the Chandra Deep Field South that totalled 31 arcmin$^2$ down to a flux density of 1740 nJ. They also detected no galaxies within the fields down to a limiting magnitude of 23.3 (5$\sigma$) with a 1 arcsec aperture.

4 PROPERTIES OF LY-$\alpha$ EMITTERS

4.1 Extracting a mass-to-‘observed light’ ratio

Can we infer anything about properties of the Ly-$\alpha$ emitters discovered in these narrow-band surveys? Is the lack of detections in the fields above $z > 7$ expected, or should we expect many more galaxies?

In equation (6), the only free parameter was the mass-to-‘observed light’ ratio, $M/L_{\text{hot}}$. Therefore, we vary $M/L_{\text{hot}}$ to give a model that is consistent with observations. The number of galaxies drops as $M/L_{\text{hot}}$ increases. (See Fig. 2) As the mass-to-light ratio increases, the star formation is spread out over a longer period of time. Therefore, the galaxies are dimmer because less stars are shining at any given time.

We find that the Subaru data at $z = 5.7$ and 6.5 are consistent with no evolution of properties of Ly-$\alpha$ emitters or the IGM opacity. The evolution in the number density of Ly-$\alpha$ emitters can be explained solely by the evolution of the halo mass function. These points have been made already by Malhotra & Rhoads (2004), Dijkstra, Lidz & Wyithe (2007a) and McQuinn et al. (2007). At $z = 5.7$, we...
find that $M_h/L_{\text{band}} = 95–120$ fits the Subaru data from Shimakata et al. (2006), with lower values favoured near the flux density limit, where it is harder to correct for sample completeness. At $z = 6.56$, a slightly (20 per cent) smaller value, $M_h/L_{\text{band}} = 85–100$, fits the Subaru data from Kashikawa et al. (2006). (These are fit for the values of $L_{\text{band}}$ below $10^{46}$ erg s$^{-1}$ to the flux density limit, for most of the observational data fall between these limits.)

The high value of $M_h/L_{\text{band}} = 95–120$ at $z = 5.7$ seems to fall outside the Poisson error at $z = 6.56$ near the flux density limit, although at higher fluxes its statistical significance is more questionable. If we take this $\sim 20$ per cent decrease in $M_h/L_{\text{band}}$ seriously, an interesting conclusion may be drawn. First of all, the decrease in $M_h/L_{\text{band}}$ from $z = 5.7$ to 6.56 is qualitatively inconsistent with the evolution of neutral fraction in the IGM. If the IGM was more neutral (i.e. less ionized) in the past, we should observe the increase in $M_h/L_{\text{band}}$ at higher $z$. The evolution in $M_h/L_{\text{band}}$ may be even more significant than it looks now, once the redshift effect is taken into account. Since the survey at $z = 6.56$ collects less photons than that at $z = 5.7$ for a given bandwidth of the instrument, one must take into account the bandwidth properly before making a quantitative comparison between $M_h/L_{\text{band}}$ from two different redshifts. We will perform this analysis more carefully in Section 4.4.

Our finding may suggest that (i) Ly$\alpha$ emitters at $z = 6.56$ are brighter intrinsically than those at $z = 5.7$, or (ii) the intrinsic luminosity is the same, but more Ly$\alpha$ photons escaped from galaxies at $z = 6.56$ than from $z = 5.7$. (The absorption in the IGM was kept the same.) The possibility (ii) is quite plausible, if dust content of galaxies at $z = 6.56$ is less than that at $z = 5.7$. How much less requires a more careful analysis, which we will give in Section 4.4.

In order to put better constraints on the bright end of the luminosity function, a larger survey is needed. The brightest Ly$\alpha$ emitter detected at $z = 5.7$ had a narrow-band magnitude of 23.41 and the brightest at $z = 6.56$ had a narrow-band magnitude of 24.13. To detect brighter Ly$\alpha$ emitters, a larger survey would be needed that could find the rare, high-density peaks of the mass function. In order to detect 10 galaxies above a magnitude of 23.41 at $z = 5.7$, the survey would need to be at least 6.34 degree$^2$ if we assume $M_h/L_{\text{band}} = 85–100$, and at least 3.13 degree$^2$ if we assume a $M_h/L_{\text{band}} = 95$. For the Subaru field at $z = 6.56$, to detect 10 galaxies with a narrow-band magnitude of 24.13 or higher, the area of the survey would have to be 3.6 degree$^2$ if we assume a $M_h/L_{\text{band}} = 100$ and 2.2 degree$^2$ if we assume a $M_h/L_{\text{band}} = 85$.

The LALA data (Rhoads et al. 2004) also probe a very similar redshift, $z = 6.55$. Since only one galaxy was found from LALA, the Poisson error is large. Nevertheless, the LALA data give us an important cross-check of the results obtained from the Subaru field at the same redshift. We find that $M_h/L_{\text{band}} = 160$ explains LALA’s detection of one galaxy at $z = 6.55$. When we compare the LALA and Subaru counts, we must take into account the different bandwidths of these surveys. The LALA’s bandwidth is about 60 per cent narrower than Subaru’s (Table 1), and thus the constraint from the LALA data would correspond to $M_h/L_{\text{band}} = 100$ for the Subaru data. We thus conclude that the constraints from the Subaru and LALA fields at $z = 6.55$ are comfortably consistent with each other. A more thorough comparison will be given in Section 4.3.

At $z = 7.0$, Iye et al. (2006) discovered one Ly$\alpha$ emitter in the Subaru field that was confirmed spectroscopically. While the Poisson error is large, we find that $M_h/L_{\text{band}} = 100$ explains Subaru’s detection of one galaxy at $z = 7.0$. This number is remarkably similar to what we have found from the Subaru fields at $z = 5.7$ and 6.56 as well as from the LALA field at $z = 6.55$. At $z = 8.76$, the searches performed in the ISAAC/VLT fields yielded null results. We therefore place lower limits to $M_h/L_{\text{band}} > 7$ and 3 from the ZEN and the ISAAC ext, respectively. The weaker constraint from the latter is due to a brighter flux density limit. These lower limits are consistent with properties of Ly$\alpha$ emitters as constrained by the other searches at $z \leq 7$.

In order to improve upon these results, how large of a survey would be needed? In order for 10 galaxies above the flux density limit to be seen in the Subaru ($z = 7.025$) and the LALA fields, the survey area would need to be increased to 2.5 and 3.4 degree$^2$, respectively. If we assume that the mass-to-light ratio and $\alpha_{\text{esc}}$ is the same at $z = 8.76$ than it is at $z = 7.025$, the survey area of the ZEN and the ISAAC ext fields would need to be increased to 24.8 and $1.69 \times 10^2$ degree$^2$, respectively. The area needed for the ISAAC ext field is larger than the entire sky, so it becomes apparent that an adjustment to the bandwidth or flux density detection limit is necessary to make finding a Ly$\alpha$ emitter more feasible.

In summary, properties of Ly$\alpha$ emitters and the IGM opacity have not evolved very much between $z = 5.7$ and 7. The lack of detection at $z = 8.76$ is also consistent with no evolution, although it does not provide a significant constraint yet.

4.2 Finding a mass-to-bolometric light’ ratio

Our analysis so far has been relatively model-independent. We have extracted the only free parameter, $M_h/L_{\text{band}}$, from various narrow-band searches of Ly$\alpha$ emitters. Here, $M_h/L_{\text{band}}$ only describes the light observed over the narrow band (the luminosity within the bandwidth, $L_{\text{band}}$, not the bolometric luminosity, $L_{\text{bol}}$). To proceed further and understand physical properties of Ly$\alpha$ emitters better, however, we must relate $M_h/L_{\text{band}}$ to the mass-to-bolometric light’ ratio, $M_h/L_{\text{bol}}$, taking into account stellar populations as well as differences in the bandwidths.

In order to get the actual mass-to-light ratio, the spectra of a stellar population of galaxies must be modelled and integrated first over all frequencies and then compared to the light that is observed in the narrow band. The fraction of Ly$\alpha$ photons that survived, $\alpha_{\text{esc}}$, also needs to be taken into account.

As a result, each data set yields a constraint on $(M_h/L_{\text{bol}})\alpha_{\text{esc}}^{-1}$ as a function of assumed stellar populations.

When the duty cycle is less than unity, the constraint should be interpreted as $(M_h/L_{\text{bol}})\alpha_{\text{esc}} e^{\gamma/2}^{-1}$, where $\gamma \sim 2$ is a local slope of the cumulative luminosity function, $N(\geq L) \propto L^{-\gamma}$, to which the current data are sensitive.

The spectra of a population of stars depend on the stellar mass spectrum and metallicity of stars. We will use a variety of mass functions paired with metallicities: (i) Salpeter (Salpeter 1955):

$$f(m) \propto m^{-2.35},$$

(ii) Larson (Larson 1998):

$$f(m) \propto m^{1} \left(1 + \frac{m}{m_c}\right)^{-1.35},$$

which matches Salpeter’s in the limit of $m_c \to 0$. One can explore a variety of models by changing one parameter, $m_c$. (iii) A top-heavy spectrum:

$$f(m) \propto \begin{cases} m^{-1}, & 100 < m < 500 M_\odot \\ 0, & \text{otherwise} \end{cases}$$

which might be possible for the primordial metal-free stars (Bromm & Larson 2004). (Note that $f(m)$ is flat for $100 < m < 500 M_\odot$.) The normalizations are given by

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The width of the line profile we adopt here is likely too broad, as
this issue further in Appendix A.

We use analytical formulae for these spectra given in section 2 of Fernandez & Komatsu (2006), paired with a line profile of Lyα.

The synthetic spectrum emerging from a galaxy with a given population of stars is the result of a variety of radiation processes.

Care must be taken when one computes the profile of Lyα line.
The width of the line profile we adopt here is likely too broad, as this profile assumes that the IGM around a source is completely neutral. The other extreme case, a delta-function profile at 10.2 eV, increases the inferred M_I/L_bol by a factor of at most a few. We study this issue further in Appendix A.

We explore three metallicities: what we refer to as Population III (Z = 0), Population II (Z = 1/50Z⊙) and Population I (Z = 1Z⊙). For convenience, we have fit the theoretical stellar data for bolometric luminosity, stellar temperature, lifetime and number of ionizing photons. The fitting functions, given in Table 3 and plotted in Fig. 3, have been obtained by fitting stellar models provided by the papers given in the third column of Table 3.

In Fig. 4, we show the luminosity integrated over a mass spectrum divided by the average stellar mass:

\[
\int_{m_1}^{m_2} \frac{dm}{f(m)} = 1, \quad \text{(10)}
\]

with m_1 and m_2 being the mass limits that the mass function is integrated over. We also consider a delta-function mass spectrum, with populations consisting of only 300 M⊙ stars.

The synthetic spectrum emerging from a galaxy with a given population of stars is the result of a variety of radiation processes. Some of the light from the star is converted by the nebula into the Lyα line, free–free, free–bound and two-photon.

We use analytical formulae for these spectra given in section 2 of Fernandez & Komatsu (2006), paired with a line profile of Lyα.

The fitting functions, given in Table 3 and plotted in Fig. 4, have been obtained by fitting stellar models provided by the papers given in the third column of Table 3.

In Fig. 4, we show the luminosity integrated over a mass spectrum divided by the average stellar mass:

\[
\int_{m_1}^{m_2} \frac{dm}{f(m)} = 1, \quad \text{(11)}
\]

for each component i, which includes stellar blackbody, Lyα, free–free, free–bound and two-photon.

Now we are in a position to calculate a conversion factor from L_bol to L_bol:

\[
\frac{L_{\text{band}}}{L_{\text{bol}}} = \frac{\int_{v_{\text{min}}}^{v_{\text{max}}} dv \sum_i \int_{m_1}^{m_2} L_{\nu,i} f(m) dm}{\int_{0}^{\nu_{\text{lim}}} dv \sum_i \int_{m_1}^{m_2} L_{\nu,i} f(m) dm},
\]

where v_max = ν_{2,obs}(1+z) and v_min = ν_{1,obs}(1+z) are the limiting frequencies of instruments in the rest frame of the galaxies (again assuming a rectangular bandpass), L_{ν,i} is the luminosity of each component, and m_1 and m_2 are the mass limits of the stellar mass spectrum, f(m).

In Table 4, we show L_{band}/L_bol for the various surveys. We find that L_{band}/L_bol is fairly constant over different mass spectra, but depends mainly on metallicity. Metal-free stars sustain higher temperatures as they undergo nuclear burning through the p–p chain. Because of this, their stellar spectrum is harder than stars with metals (see panels a–d in Fig. 4). Therefore, they emit more ionizing photons that can be converted by the surrounding nebula into the Lyα line. As the metallicity increases (panels e–j), the stellar temperature decreases, the stellar spectrum softens, the ionizing photon flux decreases, and thus the Lyα line is depleted for a given stellar mass. As a result, one obtains a lower L_{band}/L_bol for a higher metallicity.

Now, calculating the mass-to-bolometric light ratio of galaxies is simple: multiply the mass-to-observed light ratio (M/I/L_bol) by the ratio of observed to bolometric luminosity given in Table 4.

This is, however, not the end of story. Not all Lyα photons would escape from galaxies due to dust extinction, or from the IGM due to

Table 3. Fitting functions for the number of hydrogen ionizing photons per second, Q(H), stellar temperature of the star, T_eff, bolometric luminosity of the star, L_bol, and stellar lifetime, \(\tau_\ast\), for varying metallicities. These were obtained from stellar models from Marigo et al. (2001)6, Lejeune & Schaerer (2001)6 and Schaerer (2002)6 or the fitting functions from Schaerer (2002)6. Note that \(y \equiv \log(M/I/M_\odot)\), and log is a logarithm of base 10.

| Z       | Fitting function                                                                 | Reference |
|---------|---------------------------------------------------------------------------------|-----------|
| 0       | \(\log(Q(H)/\text{km}^{-1})\)                                                   | d         |
|         | \(3.64 + 1.50y - 0.556y^2 + 0.070y^3\) for \(M_\ast < 9 M_\odot\)            | c         |
|         | \(3.87 + 0.937y - 0.156y^2\) for \(M_\ast < 10 M_\odot\)                    | a         |
|         | \(0.457 + 3.90y - 0.530y^2\) for \(M_\ast \geq 10 M_\odot\)                 | c         |
|         | \(0.219 + 4.51y - 0.923y^2\) for \(M_\ast < 10 M_\odot\)                    | a         |
|         | \(9.79 - 3.76y + 1.41y^2 - 0.386y^3\) for \(M_\ast \geq 10 M_\odot\)         | c         |
| 1/50Z⊙ | \(\log(T_{\text{eff}}/\text{K})\)                                              | a         |
|         | \(27.80 + 30.68y - 14.80y^2 + 2.50y^3\) for \(M_\ast \geq 5\)               | d         |
The outcome of our analysis is a mass-to-bolometric light ratio divided by a Ly\textsubscript{α} survival fraction of Ly\textsubscript{α} (previous section, the Ly\textsubscript{α} line diminishes in strength and (\textit{M}/L\textsubscript{bol})\textsubscript{\textit{esc}}\textsubscript{\textit{α}} drops as metallicity increases. A variation due to different stellar mass spectra is negligible. The values of (\textit{M}/L\textsubscript{bol})(\textit{α}_{\text{esc}}e^{1/γ})\textsuperscript{-1} inferred from the current data processed through our simple model are rather reasonable: for all cases where at least one source is found per field, the inferred (\textit{M}/L\textsubscript{bol})(\textit{α}_{\text{esc}}e^{1/γ})\textsuperscript{-1} falls between 9 and 38, the low and high values being for the solar and zero metallicity, respectively. Consistency across redshifts (\textit{z} = 5.7, 6.5 and 7.0) as well as across different observations is striking.

We conclude from these results that the Ly\textsubscript{α} emitters detected in these narrow-band surveys are either normal galaxy populations with \textit{M}/\textit{L}\textsubscript{bol} \sim 10 and having a fair fraction of Ly\textsubscript{α} photons escape, \textit{α}_{\text{esc}1/γ} \sim 0.5–1, or starburst galaxies with \textit{M}/\textit{L}\textsubscript{bol} \sim 0.1–1 and a smaller fraction of the Ly\textsubscript{α} photons escaped from the galaxies themselves and the surrounding IGM, \textit{α}_{\text{esc}1/γ} \sim 0.01–0.05. Note that

\begin{equation}
\text{EW} = \frac{\text{Total Flux in Ly}\alpha}{\text{Continuum Flux at 1216 Å}}.
\end{equation}

Using the zero-age main-sequence values for the luminosity (given in Table 3), we obtain EWs of 1300–1700 for \textit{Z} > 0.5, or \textit{Z} = 1/50 \textit{Z}_\odot, and 220–260 for \textit{Z} = 1 \textit{Z}_\odot. Therefore, a low-survival fraction, \textit{α}_{\text{esc}} \sim 0.1, is required for low-metallicity populations, while a high \textit{α}_{\text{esc}} \sim 0.5 is required for high metallicity ones, in order to fit the observed EW. However, as the age of stars within the galaxy increases, the fraction of ionizing photons to non-ionizing photons decreases, and thus less photons are converted into Ly\textsubscript{α} photons. Therefore, the EW may decrease with time – depending on the age of the galaxy and the rate of star formation (Charlot & Fall 1993; Leitherer et al. 1999; Kudritzki et al. 2000; Malhotra & Rhoads 2002; Schaerer 2003).

Assuming the zero-age main-sequence luminosity of the stars, there are two solutions left for \textit{ε} \sim 1: (i) Ly\textsubscript{α} emitters at \textit{z} \geq 5.7 are normal populations with \textit{Z} > 1/50 \textit{Z}_\odot and \textit{α}_{\text{esc}} > 0.5, or (ii) they are starburst populations with \textit{Z} < 1/50 \textit{Z}_\odot and \textit{α}_{\text{esc}} < 0.1. As ages star, the EW of the population will also decrease, allowing for larger values of \textit{α}_{\text{esc}} for a \textit{Z} < 1/50 \textit{Z}_\odot population. For \textit{ε} < 1 other solutions are still allowed.
Mass-to-light ratio of Ly α emitters

Figure 4. Rest-frame spectra of galaxies with various populations of stars integrated over a mass spectrum. The vertical axis is in units of erg s$^{-1}$ Hz$^{-1}$ M$_{⊙}^{-1}$. The solid lines show the total spectra, while the dotted, short dashed, dot–dashed, dot–dot–dot–dashed and long dashed lines show the free–free, free–bound, stellar, Ly α and two-photon emission, respectively. We have adopted a Ly α profile from Loeb & Rybicki (1999), Santos et al. (2002). (For further discussion of the profile, see Appendix A.) We show the luminosity averaged over various mass spectra, given in Section 4, divided by the mean stellar mass. The spectra are computed for a galaxy at $z = 7.025$, although the redshift affects the shape of the Ly α line profile only. The EW of the Ly α line before extinction or scattering is also given. The EW has been computed from $\text{EW} = (\text{Total flux in Ly } α) / (\text{Continuum flux at 1216 Å})$.

Having the Ly α line be diminished in flux by about an order of magnitude is not a surprising effect. Both the IGM and galaxies themselves are expected to scatter or absorb Ly α photons efficiently. Dijkstra et al. (2007a) claim that the asymmetry in Ly α lines that has been seen in the current data already suggests that the IGM only transmitted 10–30 per cent of the Ly α flux. Several authors model the effect of dust (Hansen & Oh 2006; Verhamme, Scherer & Masell 2006) and neutral hydrogen (Laursen & Sommer-Larsen 2007) within galaxies on Ly α photons, and find that even a small amount of dust can easily absorb Ly α photons, and the resulting line profiles may be complex due to a structure in the distribution of dust and outflows. In addition, high opacity near the line centre
5.7 to 6.5. We saw this trend in the preliminary analysis based on cosmological simulations. Once the Universe is almost totally reionized, there will not be much suppression of the Lyα line, but before then, Lyα luminosity might be able to help probe the size of H II bubbles – the larger the bubble, the less suppression of the Lyα line (Haiman & Cen 2005).

The physics of this problem is complex; however, our results are consistent with a depletion of the Lyα line, but perhaps due to less dust content (Haiman & Spaans 1999). An alternative possibility is that $M_{b}/L_{bol}$ was lower in the past, that is, the Lyα emitters were intrinsically brighter at higher $z$, perhaps due to a more intense starburst. Such a burst would create a large H II bubble around the source, which also helps to increase $a_{esc}$ by suppressing the IGM opacity. It therefore seems easy to explain the 20–30 per cent decrease in $(M_{b}/L_{bol})(a_{esc}^{1/7})^{-1}$ from $z = 5.6$ to 6.5. A similar trend has also been pointed out by Stark et al. (2007).

4.4 Interesting features

Is there any `anomaly'? Let us focus on the Subaru fields at $z = 5.7$ and 6.56, as these are the most accurate data sets. We observe nearly 20–30 per cent decrease in $(M_{b}/L_{bol})(a_{esc}^{1/7})^{-1}$ from $z = 5.7$ to 6.56. We saw this trend in the preliminary analysis based upon $M_{b}/L_{bol}$ in Section 4.1. After a more careful analysis, we still observe the same trend.

Although subtle, if this is indeed a real effect, what would be the implication? This effect cannot be explained by having a smaller $a_{esc}$ (hence, a larger opacity for Lyα photons) at higher $z$. Therefore, it is inconsistent with neutral fraction in the IGM around sources being higher at higher $z$. On the contrary, one needs to have a larger $a_{esc}$ – hence, a smaller opacity for Lyα photons – at higher $z$, perhaps due to a delta function at 10.2 eV.

Another interesting feature in Table 5 is that $(M_{b}/L_{bol})(a_{esc}^{1/7})^{-1}$ at $z = 5.65$ for $Z = 0$ agrees with that at $z = 5.7$ for $Z = 1/50Z_{\odot}$ and $Z = 1Z_{\odot}$, perhaps due to a more intense starburst. Such a burst would create a large H II bubble around the source, which also helps to increase $a_{esc}$ by suppressing the IGM opacity. It therefore seems easy to explain the 20–30 per cent decrease in $(M_{b}/L_{bol})(a_{esc}^{1/7})^{-1}$ from $z = 5.7$ to 6.5. A similar trend has also been pointed out by Stark et al. (2007).

As we show in Appendix A, the magnitude of this effect is reduced to 10–20 per cent if we assume that a line profile of Lyα photons is a delta function at 10.2 eV.

Another interesting feature in Table 5 is that $(M_{b}/L_{bol})(a_{esc}^{1/7})^{-1}$ at $z = 5.65$ for $Z = 0$ agrees with that at $z = 5.7$ for $Z = 1/50Z_{\odot}$ and $Z = 1Z_{\odot}$, perhaps due to a more intense starburst. Such a burst would create a large H II bubble around the source, which also helps to increase $a_{esc}$ by suppressing the IGM opacity. It therefore seems easy to explain the 20–30 per cent decrease in $(M_{b}/L_{bol})(a_{esc}^{1/7})^{-1}$ from $z = 5.7$ to 6.5. A similar trend has also been pointed out by Stark et al. (2007).

5 COMPARISON WITH PREVIOUS WORK

A halo mass function as a tool for calculating the luminosity function of Lyα emitters is not a new idea (e.g. Haiman & Spaans 1999; Haiman et al. 2000).

Novelty of our approach is the use of the mass-to-light ratio as a fundamental parameter, which has a few advantages. In this section, we make this point clear by comparing our results with recent work on a similar subject.

Table 4. Ratio of luminosity observed within the bandwidths of Subaru ($L_{Sub,z=5.7}$, Shimazaki et al. 2006; $L_{Sub,z=6.56}$, Taniguchi et al. 2005; Kashikawa et al. 2006; $L_{Sub,z=7}$, Iye et al. 2006), LALA ($L_{LALA}$, Rhoads et al. 2004), and ZEN and ISAAC ext ($L_{ISAAC}$, Willis & Courbin 2005; Willis et al. 2006; Cubit et al. 2007) in comparison to the bolometric luminosity, $L_{bol}$, for a variety of mass spectra and metallicities, in the absence of absorption or extinction of Lyα. The ratio is nearly independent of stellar mass spectra, while it drops as the metallicity of stars increases.

| Metallicity ($Z_{\odot}$) | $f(m)$ | $L_{Sub,z=5.7}/L_{bol}$ | $L_{LALA}/L_{bol}$ | $L_{Sub,z=6.56}/L_{bol}$ | $L_{Sub,z=7}/L_{bol}$ | $L_{ISAAC}/L_{bol}$ |
|--------------------------|--------|-------------------------|---------------------|--------------------------|------------------------|---------------------|
| 0                        | 300 M$_{\odot}$ | 0.312                  | 0.209               | 0.263                    | 0.297                  | 0.120               |
| 0                        | Heavy 100, 500  | 0.311                  | 0.209               | 0.262                    | 0.297                  | 0.120               |
| 0                        | Larson, $m_{z} = 50 M_{\odot}$ 0.8, 150 | 0.313                  | 0.210               | 0.264                    | 0.299                  | 0.120               |
| 0                        | Larson, $m_{z} = 10 M_{\odot}$ 0.8, 150 | 0.305                  | 0.205               | 0.257                    | 0.291                  | 0.117               |
| 0                        | Salpeter 0.8, 150 | 0.293                  | 0.197               | 0.247                    | 0.280                  | 0.113               |
| 1/50                     | Larson, $m_{z} = 50 M_{\odot}$ 0.8, 150 | 0.219                  | 0.146               | 0.185                    | 0.210                  | 0.0843              |
| 1/50                     | Larson, $m_{z} = 10 M_{\odot}$ 0.8, 150 | 0.209                  | 0.139               | 0.176                    | 0.201                  | 0.0806              |
| 1/50                     | Salpeter 0.8, 150 | 0.189                  | 0.131               | 0.167                    | 0.190                  | 0.0761              |
| 1                        | Larson, $m_{z} = 50 M_{\odot}$ 0.8, 120 | 0.143                  | 0.0945              | 0.121                    | 0.138                  | 0.0555              |
| 1                        | Larson, $m_{z} = 10 M_{\odot}$ 0.8, 120 | 0.134                  | 0.0881              | 0.113                    | 0.130                  | 0.0519              |
| 1                        | Salpeter 0.8, 120 | 0.124                  | 0.0813              | 0.105                    | 0.120                  | 0.0480              |

Table 5. The mass (total halo mass) to light (bolometric luminosity) ratio times $1/(a_{esc}^{1/7})$. The luminosity refers to the intrinsic luminosity before absorption or extinction of Lyα photons. For each metallicity of stellar populations ($Z = 0$, $Z = 1/50Z_{\odot}$ and $Z = 1Z_{\odot}$), a range of values represents a range of stellar mass spectra. For the observational data, we used $M_{b}/L_{bol}$ = 95–120 and 85–100 for the Subaru fields at $z = 5.7$ and 6.56, respectively, whereas we used $M_{b}/L_{bol}$ = 160 and 100 for the LALA field at $z = 6.55$ and the Subaru field at $z = 7.025$. The latter values are much more uncertain than the former ones due to a large Poisson error, as only one Lyα emitter was found in each of the latter fields. For the ZEN and the ISAAC fields only lower limits are given, as no sources were found in these fields. Note that $\gamma \sim 2$ for the surveys listed here.

| Field     | Redshift | $M_{b}/L_{bol} a_{esc}^{1/7}(Z = 0)$ | $M_{b}/L_{bol} a_{esc}^{1/7}(Z = 1/50Z_{\odot})$ | $M_{b}/L_{bol} a_{esc}^{1/7}(Z = 1Z_{\odot})$ |
|-----------|----------|----------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Subaru    | 5.7      | 28–38                                  | 21–23                                         | 12–17                                         |
| LALA      | 6.55     | ~32–34                                 | ~31–23                                        | ~13–15                                        |
| Subaru    | 6.56     | 21–26                                  | 14–19                                         | 8.9–12                                        |
| Subaru    | 7.025    | ~28–30                                 | ~19–21                                        | ~12–14                                        |
| ZEN       | 8.76     | >0.79–0.84                             | >0.53–0.59                                    | >0.34–0.39                                    |
| ISAAC ext | 8.76     | >0.34–0.36                             | >0.23–0.25                                    | >0.14–0.17                                    |
In addition, our analysis is new in that we have explored various assumptions about metallicity and stellar mass spectra of Lyα emitters.

5.1 Dijkstra et al. (2007b)

Dijkstra et al. (2007b) computed \( N(>F) \) by integrating the halo mass function over mass above a certain flux density, \( F \). In order to relate the host halo mass to the observed luminosity, \( L_\text{esc} \), they used

\[
\frac{M_\text{h}}{L_\text{esc}} = 0.128 \times \frac{t_{\text{sys}}/(100 \text{ Myr})}{\Omega_{\text{esc}}/(\Omega_0 \gamma_{\text{esc}})},
\]

which is their equation (2) in their notation. (Note that in our notation \( M/L \) is always measured in units of \( M_\odot \ L_\odot^{-1} \).) Here, \( \eta \) is the fraction of baryon mass converted into stars, \( t_{\text{sys}} = \epsilon \ t_{\text{Hubble}} \) is the duration of a starburst, \( t_{\text{Hubble}} \) is the Hubble time and \( \epsilon \) is the duty cycle.

In our approach, \( M_\text{h}/L_\text{esc} \) is the only free parameter and the effect of \( \epsilon \) is included using the degeneracy line, \( (M_\text{h}/L_\text{esc}) e^{-1/\gamma} = \text{constant} \). Their approach was to divide \( M_\text{h}/L_\text{esc} \) up further by introducing two free parameters, \( \epsilon \) and \( \eta \), and constrain these parameters simultaneously. However, it is difficult to extract more than \( M_\text{h}/L_\text{esc} \) from the observed luminosity function. Fig. 1 of Dijkstra et al. (2007b) also shows that \( \epsilon \) and \( \eta \) are strongly degenerate. In our opinion, the current data do not allow for two free parameters to be constrained well. In addition, the use of \( M_\text{h}/L_\text{esc} \) as a parameter avoids the need to specify the duration of a starburst or the fraction of baryon mass converted into stars.

They found that \( \alpha_{\text{esc}} \) at \( z = 5.7 \) inferred from Shimasaku et al. (2006) and \( \alpha_{\text{esc}} \) at \( z = 6.5 \) inferred from Taniguchi et al. (2005), Kashikawa et al. (2006) are about the same, the ratio of the two being \( \alpha_{\text{esc},5.7}/\alpha_{\text{esc},6.5} \approx 0.8-1.5 \) for a prior on \( \epsilon \) of \( 0.5-0.03 \). We would find \( \alpha_{\text{esc},5.7}/\alpha_{\text{esc},6.5} \approx 0.7-0.8 \) (see Table 5), if we assumed that the intrinsic properties of Lyα emitters did not change between these redshifts. The other values of \( \alpha_{\text{esc}} \) are permitted when we vary the intrinsic mass-to-light, \( M_\text{h}/L_{\text{bol}} \), with \( (M_\text{h}/L_{\text{bol}})(\alpha_{\text{esc}}/1)^{-1} \) held fixed. This is essentially equivalent to their varying \( \epsilon \) along the degeneracy line.

When an additional constraint from the luminosity function of ultraviolet (UV) continuum was included in the analysis, they found that the constraints shifted slightly to \( \alpha_{\text{esc},5.7}/\alpha_{\text{esc},6.5} \approx 1.1-1.8 \). While we do not perform a joint analysis with the UV continuum luminosity function in this paper, we would expect a similar shift in the parameter constraint.

5.2 Salvaterra & Ferrara (2006)

Salvaterra & Ferrara (2006) used an stellar mass spectrum of stars that is given by a delta function at \( m_* = 300 M_\odot \), and related \( M_\text{h} \) to \( L_{\text{band}} \) as

\[
\frac{M_\text{h}}{L_{\text{band}}} = \int_{m_{\text{min}}}^{m_{\text{max}}} \frac{1}{dV} \sum_i L_i (300 M_\odot) \frac{1}{\Omega_i/(\Omega_0 \gamma_i)},
\]

which can be obtained from their equation (3), combined with our equation (4). Their \( M_\text{h}/L_{\text{band}} \) is therefore equal to about 10 times\(^2\) the mass-to-light of a metal-free star of 300 \( M_\odot \).

The lifetime of a starburst of their model galaxy is as short as the lifetime of stars, which is only 2 Myr. In other words, they assumed that these massive stars formed at once in a galaxy, so that the lifetime of starbursts was the shortest possible time, equal to the lifetime of the star. This creates a very short-lived but extremely bright galaxy that could easily be detected with current observations.

The mass-to-bolometric light ratio of their model galaxy was \( M_\text{h}/L_{\text{bol}} = 6.73 \times 10^{-4} \) and \( 1.35 \times 10^{-3} \) for ‘H-cooling’ and ‘H2-cooling’ haloes, respectively, assuming all Lyα photons escaped. (They used \( \eta = 0.8 \) and 0.4 for H-cooling and H2-cooling haloes, respectively.) These extreme values allow them to predict that there should be thousands of galaxies seen in the NICMOS Ultra Deep Field, where only three or fewer were actually detected, and 400 to 700 in the ZEN field, where no sources were detected. They also reported that almost all of the Spitzer counts should be attributed to galaxies above \( z \sim 8 \).

Their conclusion is driven by their fixed value of \( M_\text{h}/L_{\text{bol}} \), which seems rather low. Our formulation, which treats \( M_\text{h}/L_{\text{bol}} \) as a free parameter, allows for dimmer galaxies by spreading out the star formation over a much longer period than the stellar lifetime. This allows us to obtain results that are consistent with observations. Note that their using a delta-function mass spectrum is not the source of discrepancy. We can still fit the observations with a reasonable \( M_\text{h}/L_{\text{bol}} \) for the same mass spectrum. The source of discrepancy is their assumption about an instantaneous starburst in 2 Myr.

They used these bright galaxies to fit the observed excess in the near-infrared background. The main conclusion of Salvaterra & Ferrara (2006) is that the excess near-infrared background cannot be mainly coming from high-z galaxies at \( z \gtrsim 7 \), as they do not see these extremely bright galaxies in the NICMOS UDF, ZEN or Spitzer counts.

However, their argument does not rule out the high-z galaxies being the origin of the near-infrared background. Using a simple argument based upon energy conservation, we have shown in the previous paper (Fernandez & Komatsu 2006) that the near-infrared background measures only the total light integrated over time, and thus one can obtain the same amount of near-infrared background by having either (i) extremely bright sources over an extremely short-time period, such as those invoked by Salvaterra & Ferrara (2006), or (ii) much dimmer sources over a much longer time period. While Salvaterra & Ferrara (2006) have successfully shown that the first possibility is ruled out, they have not ruled out the second possibility yet.

5.3 Le Delliou et al. (2006)

Le Delliou et al. (2006) predict the luminosity functions of Lyα emitters at redshifts from \( 3 < z < 6.6 \), using cosmological simulations coupled with a semi-analytical galaxy formation model.

Similar to ours and the other work, they assume that the escape fraction of Lyα photons are independent of halo mass, and find its value, \( \alpha_{\text{esc}} = 0.02 \), by fitting the observed luminosity function of Lyα emitters at \( z \sim 3 \). (See Kobayashi, Totani & Nagashima 2007, for a criticism on this assumption.)

Since the halo mass function is also an essential ingredient in the semi-analytical galaxy formation model, and they make the same assumption about the escape fraction of Lyα photons, we expect our predictions and theirs to agree well for the same set of parameters.

We find that we can fit the bright end of their predicted luminosity functions (their Fig. 1 for \( z = 7 \)) with a population of starburst galaxies, \( M_\text{h}/L_{\text{bol}} \sim 1 \), which is a very reasonable result.

We believe that our simple model captures the basic physics that goes into their model, which is much more sophisticated and complex. At a fainter end, however, their luminosity function flattens out and our calculations always overpredict the number of sources. This

---

\(^{1}\) Their luminosity, \( L_\text{esc} \), is different from our \( L_{\text{band}} \) as they ignored the line profile, continuum and bandwidth of instruments.  

\(^{2}\) \( \Omega_i/(\Omega_0 \gamma_i) \sim 10 \).
is likely due to our assumption about a constant mass-to-light ratio. It is expected that this assumption breaks down once a large mass range is included in the analysis. The most economical way to improve our model is to introduce a second free parameter, a slope of mass-to-light, such that $L \propto M^p$, for instance. As the observations improve in the future, a two-parameter model such as this should be used.

6 CONCLUSIONS

A simple model based upon the halo mass function coupled with a constant mass-to-light ratio fits the luminosity functions measured and constrained by the current generation of narrow-band Ly$\alpha$ surveys from $5.7 \lesssim z \lesssim 8.8$. We have explored various metallicities and stellar mass spectra.

The inferred mass-to-light ratios are consistent with no evolution in the properties of Ly$\alpha$ emitters or opacity in the IGM from $5.7 \lesssim z \lesssim 7$. Therefore, the current data of the luminosity functions do not provide evidence for the end of reionization. The data at $z = 8.8$ do not yield a significant constraint yet.

These mass-to-light ratios suggest that the Ly$\alpha$ emitters discovered in the current surveys are either starburst galaxies with only a smaller fraction of Ly$\alpha$ photons escaped from galaxies themselves and the IGM, $\alpha_{\text{esc}} e^{1/\beta} \sim 0.01$–0.05, or normal populations with a fair fraction of Ly$\alpha$ photons escaped, $\alpha_{\text{esc}} e^{1/\beta} \sim 0.5$–1. The luminosity function alone cannot distinguish between these two possibilities.

For the duty cycle of order unity, $\epsilon \sim 1$, the observed EW of Ly$\alpha$ line indicates that starburst populations are consistent with low-metallicity populations with $Z < 1/50 Z_{\odot}$, while normal populations are consistent with high-metallicity populations. The other solutions are still allowed for $\epsilon < 1$. Note that a recent study of the SED of Ly$\alpha$ emitters by Nilsson et al. (2007) shows that the Ly$\alpha$ emitters at $z = 3.15$ are consistent with a very low-metallicity population, $Z = 1/200 Z_{\odot}$.

To constrain the properties of Ly$\alpha$ emitters further, one should use asymmetry absorption features of the measured Ly$\alpha$ line profiles to distinguish between them (Miralda-Escude 1998; Miralda-Escude & Rees 1998; Haiman 2002; Santos 2004; Tasitsiomi 2006). The best way to break degeneracy between $\epsilon$ and $\alpha_{\text{esc}}$ is to detect the deviation of the cumulative luminosity function from a pure power law. In order to do this it is crucial to determine the bright end of luminosity function more accurately.

We disagree with the conclusion reached by Salvaterra & Ferrara (2006) that no detection of Ly$\alpha$ emitters at $z = 8.8$ excludes the excess near-infrared background being produced by galaxies at $z > 7$. While they have excluded the excess background coming from extremely bright starburst galaxies with $M_{\text{bol}}/L_{\text{bol}} \sim 10^{-3}$ and the lifetime of 2 Myr, their argument does not exclude another possibility that the excess background originates from galaxies with $M_{\text{bol}}/L_{\text{bol}} \sim 0.1$–1 and the lifetime comparable to the age of the Universe at $z > 7$. As the near-infrared background measures only the total amount of light integrated over time, both scenarios result in the same amount of background light. As we have shown in this paper, the latter scenario is consistent with all the existing Ly$\alpha$ surveys from $5.7 \lesssim z \lesssim 8.8$.

There is a subtle hint that 20–30 per cent more Ly$\alpha$ photons survived from $z = 6.5$ than from $z = 5.7$. A number of factors need to be checked carefully before this conclusion is taken seriously: the completeness correction and spectroscopic confirmation rate of the observed luminosity function, the shape of Ly$\alpha$ line profiles (which is, however, not quite enough to make the effect go away; see Appendix A), and accuracy of the evolution of the theoretical halo mass function in these redshifts. In addition, more elaborated theoretical models such as those described in Section 2.1 may be necessary to test reality of this effect, while it is interesting that the model with a duty cycle has also shown a similar trend (Stark et al. 2007).

Our method should provide a simple tool for interpreting the galaxy number count data in terms of the mass-to-light ratio. Or, for a given mass-to-light ratio as constrained by the existing data, it can also be used to predict the luminosity functions, and thus it helps to design future Ly$\alpha$ surveys such as a follow-up survey at $z = 7$ with Subaru, at $z = 8.8$ with VLT and a new survey at even higher redshifts with the James Webb Space Telescope (see also Barton et al. 2004, for an alternative way of making forecasts).

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APPENDIX A: ON THE PROFILE OF Lyα LINES

Throughout this paper, we have adopted a theoretical line profile computed by Loeb & Rybicki (1999) and later fit by Santos et al. (2002) (their equation 15). This line profile is fairly broad (see dot–dot–dot–dashed lines in Fig. 4). The physical origin of this broadening is a combination of the IGM scattering and cosmological redshift. Since their underlying assumption that the IGM around sources is neutral may not be always valid, a care must be taken when one uses their theoretical profiles. The broadening is reduced significantly when the IGM around sources is ionized.

The shape of the line profile affects our analysis through the bandwidths of instruments. Since we are dealing with narrow-band filters, instruments miss a large fraction of Ly photons if a line profile is broader than their bandwidths. Therefore, if we assumed erroneously that the line profile was too broad then the inferred $M_L/L_{bol}$ would be too low.

In order to quantify a possible uncertainty regarding the shape of the line profile, we explore the extreme case where a line profile is a delta function at 10.2 eV. Since the instruments would not miss any Ly photons, the luminosity within the band, $L_{band}$, would increase.

Table A1 shows that a delta-function line profile increases the luminosity within instrument’s bandwidths substantially. For metal-free stars with a heavy mass spectrum, the luminosity increases by a factor of 2 for Subaru, a factor of 3 for LALA and a factor of 5.5 for ISAAC.

In Table A2, we report the inferred $(M/L_{bol})(\alpha_{esc} e^{-t/\gamma})^{-1}$ from assuming a delta-function line profile. These values should be compared with those in Table 5. While there are changes in the inferred $(M/L_{bol})(\alpha_{esc} e^{-t/\gamma})^{-1}$ at the level of a factor of a few, the main result from our analysis does not change: the Lyα emitters discovered in these surveys are either starburst galaxies with $\alpha_{esc} e^{-t/\gamma} \sim 0.01$–0.1 or normal galaxies with $\alpha_{esc} e^{-t/\gamma} \sim 0.5$–1.

On the other hand, a hint that $(M/L_{bol})(\alpha_{esc} e^{-t/\gamma})^{-1}$ at $z = 5.56$ is smaller than that at $z = 5.7$ is now less significant: it’s only a 10–20 per cent effect rather than a 20–30 per cent effect.
Table A1. The same as Table 4, but for a Lyα line profile being a delta function at 10.2 eV. Small differences between observations are due to differences in the continuum flux within bandwidths.

| Metallicity (Z⊙) | m(m) | f(m) | lαesc,0 | lαesc,50 | lαesc,1 | lαesc,1/50 |
|------------------|------|------|---------|----------|--------|-----------|
| 0 300 M⊙δ-function | –    | 0.667| 0.662   | 0.665    | 0.668  | 0.661     |
| Heavy           | 100, 500 | 0.666| 0.662   | 0.665    | 0.668  | 0.661     |
| Larson, m⊙ = 50 M⊙ | 0.8, 150 | 0.673| 0.668   | 0.671    | 0.674  | 0.667     |
| Larson, m⊙ = 10 M⊙ | 0.8, 150 | 0.644| 0.639   | 0.643    | 0.646  | 0.638     |
| Salpeter        | 0.8, 150 | 0.603| 0.598   | 0.601    | 0.604  | 0.597     |
| Larson, m⊙ = 50 M⊙ | 0.8, 150 | 0.385| 0.378   | 0.383    | 0.387  | 0.377     |
| Larson, m⊙ = 10 M⊙ | 0.8, 150 | 0.362| 0.354   | 0.359    | 0.363  | 0.353     |
| Salpeter        | 0.8, 150 | 0.326| 0.334   | 0.331    | 0.336  | 0.325     |
| Larson, m⊙ = 50 M⊙ | 0.8, 120 | 0.218| 0.209   | 0.215    | 0.220  | 0.207     |
| Larson, m⊙ = 10 M⊙ | 0.8, 120 | 0.200| 0.192   | 0.197    | 0.202  | 0.190     |
| Salpeter        | 0.8, 120 | 0.182| 0.174   | 0.179    | 0.184  | 0.172     |

Table A2. The same as Table 5, but for a Lyα line profile being a delta function at 10.2 eV.

| Field     | Redshift | m⊙ | [1312]/(Z⊙ = 0) | m⊙ | [1312]/(Z⊙ = 1/50) | m⊙ | [1312]/(Z⊙ = 1) |
|-----------|----------|----|----------------|----|-------------------|----|----------------|
| Subaru    | 5.7      | 57–81 | 31–46        | 17–26 |
| LALA      | 6.55     | ~96–107 | ~53–60   | ~28–33 |
| Subaru    | 6.56     | 51–67   | 28–38     | 15–22 |
| Subaru    | 7.025    | ~60–67  | ~34–39   | ~18–22 |
| ZEN       | 8.76     | >4.2–4.7 | >2.3–2.6 | >1.2–1.4 |
| ISAAC ext | 8.76     | >1.8–2.0 | >0.98–1.1 | >0.52–0.62 |

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