Very massive stars in high-redshift galaxies

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ABSTRACT
A significant fraction of Lyα-emitting galaxies (LAEs) at \( z \gtrsim 5.7 \) have rest-frame equivalent widths (EWs) greater than \( \sim 100 \) Å. However, only a small fraction of the Lyα flux produced by a galaxy is transmitted through the intergalactic medium, which implies intrinsic Lyα EWs that are in excess of the maximum allowed for a Population II stellar population having a Salpeter mass function. In this paper, we study characteristics of the sources powering Lyα emission in high-redshift galaxies. We propose a simple model for Lyα emitters in which galaxies undergo a burst of very massive star formation that results in a large intrinsic EW, followed by a phase of Population II star formation with a lower EW. We confront this model with a range of high-redshift observations and find that the model is able to simultaneously describe the following eight properties of the high-redshift galaxy population with plausible values for parameters like the efficiency and duration of star formation: (i)–(iv) the ultraviolet and Lyα luminosity functions of LAEs at \( z = 5.7 \) and 6.5, (v)–(vi) the mean and variance of the EW distribution of Lyα-selected galaxies at \( z = 5.7 \), (vii) the EW distribution of i-drop galaxies at \( z \sim 6 \), and (viii) the observed correlation of stellar age with EW. Our modelling suggests that the observed anomalously large intrinsic EWs require a burst of very massive star formation lasting more than a few to 10 per cent of the galaxy’s star-forming lifetime. This very massive star formation may indicate the presence of Population III star formation in a few per cent of i-drop galaxies, and in about half of the Lyα-selected galaxies.

Key words: galaxies: high-redshift – cosmology: theory.

1 INTRODUCTION

Narrow-band searches for redshifted Lyα lines have discovered a large number of Lyα-emitting galaxies (LAEs) with redshifts between \( z = 4.5 \) and 7.0 (e.g. Hu & McMahon 1996; Hu et al. 2002; Malhotra & Rhoads 2002; Kodaira et al. 2003; Dawson et al. 2004; Hu et al. 2004; Stanway et al. 2004; Taniguchi et al. 2005; Iye et al. 2006; Kashikawa et al. 2006; Shimasaku et al. 2006; Westra et al. 2006; Stanway et al. 2007; Tapken et al. 2007). The Lyα line emitted by these galaxies is very prominent, often being the only observed feature. The prominence of the Lyα line quantified by its equivalent width (EW), defined as the total flux of the Lyα line, \( F_{\text{Ly} \alpha} \), divided by the flux density of the continuum at 1216 Å: \( \text{EW} \equiv \frac{F_{\text{Ly} \alpha}}{F_{1216}} \). Throughout this paper, we refer to the rest-frame EW of the Lyα line (which is a factor of \( 1 + z \) lower than the EW in the observer’s frame).

Approximately 50 per cent of Lyα emitters at \( z = 4.5 \) and 5.7 have lines with EW \( \sim 100–500 \) Å (Dawson et al. 2004; Hu et al. 2004; Shimasaku et al. 2006). For comparison, theoretical studies conclude that the maximum EW which can be produced by a conventional population of stars is 200–300 Å. Moreover, this maximum EW can only be produced during the first few million years of a starburst, while at later times the luminous phase of Lyα EW gradually fades (Charlot & Fall 1993; Malhotra & Rhoads 2002). Therefore, observed EWs lie near the upper envelope of values allowed by a normal stellar population.

The quoted value for the upper envelope of EW \( \sim 200–300 \) Å corresponds to the emitted Lyα flux. However, not all Lyα photons are transmitted through the intergalactic medium (IGM), and we expect some attenuation. Within the framework of a cold dark matter cosmology, gas surrounding galaxies is significantly overdense, and possesses an infall velocity relative to the mean IGM (Barkana 2004). As a net result, the IGM surrounding high-redshift galaxies is systematically opaque to Lyα photons. Indeed it can be shown that for reasonable model assumptions, only \( \sim 10–30 \) per cent of all Lyα photons are transmitted through the IGM (Dijkstra, Lidz & Wyithe 2007a). As a result, the intrinsic Lyα EW emitted by high-redshift LAEs is systematically larger than that observed. Indeed, this observation suggests that a significant fraction of LAEs at \( z \gtrsim 4.5 \) have intrinsic EWs that are much larger than can possibly be produced by a conventional population of young stars.

One possible origin for this large-EW population is provided by active galactic nuclei (AGN), which can have much larger EWs due to their harder spectra (e.g. Charlot & Fall 1993). However,
large-EW LAEs are not AGN for several reasons: (1) the Lyα lines are too narrow (Dawson et al. 2004), (2) these objects typically lack high-ionization-state ultraviolet (UV) emission lines, which are symptomatic of AGN activity (Dawson et al. 2004), and (3) deep X-Ray observations of 101 Lyα emitters by Wang et al. (2004, also see Malhotra et al. 2003; Lai et al. 2007) revealed no X-Ray emission neither from any individual source, nor from their stacked X-Ray images.

Several recent papers have investigated the stellar content of high-redshift LAEs by comparing stellar synthesis models with the observed broad-band colours (Finkelstein et al. 2007). These comparisons are often aided by deep IRAC observations on Spitzer (Lai et al. 2007; Pirzkal et al. 2007). In this paper, we take a different approach. Instead of focusing on individual galaxies, our goal is to provide a simple model that describes the population of LAEs as a whole. This population is described by the rest-frame UV and Lyα luminosity functions (LFs) at $z = 5.7$ and 6.5, and the Lyα EW distribution at $z = 5.7$ (Kashikawa et al. 2006; Shimasaku et al. 2006). The sample of high-redshift LAEs is becoming large enough that meaningful constraints can now be placed on simple models of galaxy formation.

The outline of this paper is as follows. In Sections 2–5, we describe our models. In Section 6, we discuss our results, and compare with results from stellar synthesis models, before presenting our conclusions in Section 7. 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. 2007).

2 THE MODEL

Dijkstra, Wyithe & Haiman (2007b) found that the observed Lyα LFs at $z = 5.7$ and 6.5 are well described by a model in which the Lyα luminosity of a galaxy increases in proportion to the mass of its host dark matter $M_{\text{dark}}$. One can constrain quantities related to the star formation efficiency from such a model (also see Mao et al. 2007; Stark, Loeb & Ellis 2007).

However, it is also possible to obtain constraints from the rest-frame UV LFs. In contrast to the Lyα LF, the UV LF is not affected by attenuation by the IGM, which allows for more reliable constraints on quantities related to the star formation efficiency. In the first part of this paper (Sections 3 and 4) we present limited modelling to illustrate parameter dependences, using the UV LF to constrain model parameters related to star formation efficiency and lifetime. These model parameters may then be kept fixed, and the Lyα LFs and EW distributions are used to constrain properties of high-redshift LAEs such as their intrinsic Lyα EW and the fraction of Lyα that is transmitted through the IGM. Later, in Section 5, we present our most general model, and fit to both the UV and Lyα LFs, as well as the EW distribution, simultaneously, treating all model parameters as free.

3 MODELLING THE ULTRAVIOLET AND Lyα LUMINOSITY FUNCTIONS

3.1 Constraints from the UV LF

We begin by presenting a simple model for the UV LF (Stark et al. 2007; Wyithe & Loeb 2007). In Fig. 1, we show the rest-frame UV LFs of LAEs at $z = 5.7$ and 6.5 (Kashikawa et al. 2006; Shimasaku et al. 2006). We use the following simple prescription to relate the UV flux density emitted by a galaxy, $f_{1350}^\lambda$, to the mass of its host dark matter $M_{\text{dark}}$. The total mass of baryons within a galaxy $M_{\text{baryons}}$ is then given by

$$N(> f_{1350}^\lambda) = \epsilon_{\text{DC}} \int_{M_{\text{UV}}}^{\infty} dM \frac{dn}{dM},$$

where $M_{\text{UV}}$ is the mass that corresponds to the flux density, $f_{1350}^\lambda$ (through the relations given above). The function $dn/dM$ is the Press–Schechter (1974) mass function (with the modification of Sheth, Mo & Tormen 2001), which gives the number density of haloes of mass $M$ (in units of comoving Mpc$^{-3}$). $^1$

$^1$ Our model effectively states that the star formation rate in a galaxy increases linearly with halo mass. This is probably not correct. To account for a different mass dependence, we could write the star formation rate as $\dot{M}_* \propto M^\beta$, where $\beta$ is left as a free parameter. However, the range of observed luminosities spans only one order of magnitude, and we will show that the choice $\beta = 1$ provides a model that describes the observations well. Furthermore, the duty cycle $\epsilon_{\text{DC}}$ may be viewed as the fraction of dark matter haloes that are currently forming stars. The remaining fraction $(1 - \epsilon_{\text{DC}})$ of haloes either have not formed stars yet, or are evolving passively. In either case, the contribution of these haloes to the UV LF is set to be negligible.
parameters in our model are the duty cycle, \( \epsilon_{DC} \), of the galaxy, and the fraction of baryons that are converted into stars, \( f_i \). We calculated the UV LF for a grid of models in the \((\epsilon_{DC}, f_i)\)-plane, and generated likelihoods \( L[P] = \exp[-0.5\chi^2] \), where \( \chi^2 = \sum_{i} N_{\text{data}}(\text{model}, - \text{data})^2/\sigma_i^2 \), in which data\(_i\) and \( \sigma_i \) are the \( i \)th UV LF data point and its error, and model, is the model evaluated at the \( i \)th luminosity bin. The sum is over \( N_{\text{data}} = 8 \) data points. The inset in Fig. 1 shows the resulting likelihood contours in the \((\epsilon_{DC}, f_i)\)-plane at 64, 26 and 10 per cent of the peak likelihood. The best-fitting model has \((\epsilon_{DC}, f_i) = (0.03, 0.06)\) and is plotted as the solid line. In the following sections, we assume this combination of \( f_i \) and \( \epsilon_{DC} \).

### 3.2 Constraints from the Ly\( \alpha \) LF

We next model the Ly\( \alpha \) LF, beginning with the best-fitting model of the previous section. The number density of LAEs at redshift \( z \) with Ly\( \alpha \) luminosities exceeding \( T_\alpha \times L_\alpha \) is given by (Dijkstra et al. 2007b):

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

where the Ly\( \alpha \) luminosity and host halo mass, \( M_{\alpha} \), are related by

\[
T_\alpha \times L_\alpha = L_{\alpha} \frac{M_{\alpha}(M_\odot)/\Omega_{\text{m}}}{\Omega_{\text{b}} f_i} T_\alpha.
\]

In this relation, \( T_\alpha \) is the IGM transmission multiplied by the escape fraction of Ly\( \alpha \) photons from the galaxy, and \( L_{\alpha} = 2.0 \times 10^{42} \text{erg s}^{-1} (M_\odot \text{yr}^{-1})^{-1} \) is the Ly\( \alpha \) luminosity emitted per unit of star formation rate (in \( M_\odot \text{yr}^{-1} \)). Throughout, \( L_{\alpha,42} \) denotes \( L_{\alpha} \) in units of \( 10^{42} \text{erg s}^{-1} / (M_\odot \text{yr}^{-1}) \). We have taken \( L_{\alpha,42} = 2.0 \), which is appropriate for a metallicity of \( Z = 0.05Z_\odot \) and a Salpeter initial mass function (IMF) (Dijkstra et al. 2007). Note that when comparing to observed luminosities (Kashikawa et al. 2006; Shimasaku et al. 2006), we have replaced \( L_{\alpha} \) with \( T_\alpha \times L_\alpha \). This is because the observed luminosities have been derived from the observed fluxes by assuming that all Ly\( \alpha \) emerging from the galaxy was transmitted by the IGM, whereas there is substantial absorption (e.g. Dijkstra et al. 2007a). The product \( T_\alpha \times L_\alpha \) may be written as \( T_\alpha \times L_\alpha = 4\pi d_L (z) S_\alpha \), where \( S_\alpha \) is the total Ly\( \alpha \) flux detected on Earth and \( d_L (z) \) is the luminosity distance to redshift \( z \). The product \( T_\alpha \times L_\alpha \) may therefore be viewed as an effective luminosity inferred at Earth. Furthermore, the selection criteria used by Shimasaku et al. (2006) and Kashikawa et al. (2006) limit these surveys to be sensitive to LAEs with EW \( \geq 10 \text{Å} \). In the remainder of this paper, the EW of model LAEs is always larger than this EW\(_\text{min}\), and we need not worry about selection effects when comparing our model to the data.

In this section, we set the transmission at \( z = 6.5 \) (denoted by \( T_{\alpha,65} \)) to be a factor of \( \sim 1.2 \) lower\(^2\) than at \( z = 5.7 \) (denoted by \( T_{\alpha,57} \)). This ratio is the median of the range found by Dijkstra et al. (2007a). We then calculated the Ly\( \alpha \) LF for a range of \( T_{\alpha,57} \), and generated likelihoods \( L[P] = \exp[-0.5\chi^2] \), where \( \chi^2 = \sum_{i} N_{\text{data}}(\text{model}, - \text{data})^2/\sigma_i^2 \), for each model. Here, data\(_i\) and \( \sigma_i \) are the \( i \)th data point and its error, and model, is the model evaluated at the \( i \)th luminosity bin. The sum is over \( N_{\text{data}} = 6 \) points at each redshift. In Fig. 2, we show the Ly\( \alpha \) LFs at \( z = 5.7 \) and 6.5. The red squares and blue circles represent data from Shimasaku et al. (2006, \( z = 5.7 \)) and Kashikawa et al. (2006, \( z = 6.5 \)), respectively.

The likelihood for \( T_{\alpha,57} \) (normalized to a peak of unity) is shown in the inset. The best-fitting model is overplotted as the solid lines, for which the value of the transmission is \( T_{\alpha,57} = 0.30 \). The modelling presented in this and the previous section therefore suggests that, in order to simultaneously fit the Ly\( \alpha \) and UV LFs, only \( \sim 30 \) per cent of the Ly\( \alpha \) can be transmitted through the IGM. This transmission is in good agreement with the results obtained by Dijkstra et al. (2007a), who modelled the transmission directly and found that for reasonable model parameters the transmission must lie in the range \( 0.1 \lesssim T_\alpha \lesssim 0.3 \).

### 3.3 The predicted equivalent width

While in agreement with the observed LFs, the model described in Section 3.2 does not reproduce the very large observed EWs. The Ly\( \alpha \) luminosity can be rewritten in terms of the star formation rate (in \( M_\odot \text{yr}^{-1} \)) and UV LFs, only \( \sim 30 \) per cent of the Ly\( \alpha \) photons are transmitted through the IGM. The best-fitting models are overplotted as the solid lines.

2 For our primary results in Section 5, we allow this ratio to be a free parameter. The results presented in this section are not sensitive to the precise choice of the ratio of IGM transmission at \( z = 5.7 \) and 6.5.
4 THE FLUCTUATING IGM MODEL

The model described in Section 3 assumed that the Lyα flux of galaxies was subject to uniform attenuation by the IGM. In this section, we relax this assumption and investigate the predicted EWs in a more realistic IGM where transmission fluctuates between galaxies. We refer to this model as the ‘fluctuating IGM’ model. In this model, a larger transmission translates to a larger observed EW. As a result, galaxies with large $T_\alpha$ are more easily detected, and the existence of these galaxies may therefore affect the observed EW distribution for Lyα-selected galaxies, even in cases where they comprise only a small fraction of the intrinsic population. In this section, we investigate whether this bias could explain the anomalously large observed EW.

We assume a lognormal distribution for $T_{\alpha,57}$:

$$P(u)du = \frac{1}{\sqrt{2\pi}\sigma_u} \exp\left[\frac{-(u - \langle u \rangle)^2}{2\sigma_u^2}\right] du,$$  

where $(u) = \log(T_{\alpha,57})$ is the log (base 10) of the mean transmission and $\sigma_u$ is the standard deviation in log-space. Throughout this section, we drop the subscript ‘57’. Equation (4) may be rewritten in the form

$$f(>u) = \frac{1}{2} - \frac{1}{2\pi\sigma_u} \exp\left[\frac{-(u - \langle u \rangle)^2}{2\sigma_u^2}\right],$$  

which gives the fraction of LAEs with log $T_\alpha > u$. The number density of LAEs is then given by

$$N(> T_\alpha \times L_\alpha) = \epsilon_{\text{DC}} \int_0^\infty dM \frac{dn}{dM} f(> u(T_\alpha \times L_\alpha, M)),$$  

where

$$M_{\min}(u) = \log \left(\frac{T_\alpha \times L_\alpha}{\langle L_\alpha \rangle M_{\min}}\right).$$

Equation (6) differs from equation (2) in two ways: (1) there is no lower integration limit, and (2) there is an additional term $f(>u)$. These two differences reflect the fact that all masses contribute to the number density of LAEs brighter than $T_\alpha \times L_\alpha$, and that lower mass systems require larger transmissions (equation 7) which are less common (equation 5). In the limit $\sigma_u \rightarrow 0$, the function $f(>u)$ ‘jumps’ from 0 to 1 at $M_{\min}$ (equation 3), which corresponds to the original equation (2).

In this formalism we may also write the number density of LAEs with transmission in the range $u \pm du/2 = \log T_\alpha \pm d\log T_\alpha$, which is given by

$$N(u)du = P(u)du \int_{M_{\min}(u)}^{\infty} dM \frac{dn}{dM}.$$

Here $M_{\min}(u)$ is the minimum mass of galaxies that can be detected with a transmission in the range $u \pm du/2$ (for $M_{\min} < M_{\min}$ the total flux falls below the detection threshold). The number density of LAEs with transmission in the range $u \pm du/2$ may be used to find the number density of LAEs with EWs in the range log $\text{EW} \pm d\log \text{EW}$ via the relation $\text{EW} = 160 T_\alpha \text{ Å}$ (for the choice $L_\alpha = 20$, see Section 3.2). Equation (8) shows that the observed EW distribution takes the shape of the original transmission distribution, modulated by the boost which increases towards larger EWs.

As in Section 3.2 we assume the best-fitting model parameters for $\epsilon_{\text{DC}}$ and $f_*$ derived from the UV LFs determined in Section 3.1. We calculate model Lyα LFs on a grid of models in the $(\sigma_u, (T_\alpha))$-plane, and generate likelihoods following the procedure outlined in Section 3.2. The results of this calculation are shown in Fig. 3 where we plot the Lyα LFs together with likelihood contours in the $(\sigma_u, (T_\alpha))$-plane (inset). The best-fitting models favour no scatter in $T_\alpha$, but of a model with $(\langle T_\alpha \rangle, \sigma_u) = (0.27, 0.2)$ shown as the thick black dot in the inset. The best-fitting model to the data has $\sigma_u \sim 0$ (which corresponds to the model shown in Fig. 2).

Figure 3. The same as Fig. 2. However, instead of assuming a single value of IGM transmission $T_{\alpha,57}$, we assumed a lognormal distribution of IGM transmission with a mean of log $T_{\alpha,57}$ and standard deviation of (in the log) $\sigma_u$ (see the text). This reflects the possibility that the IGM transmission fluctuates between galaxies. The inset shows likelihood contours for $(\langle T_\alpha \rangle, \sigma_u)$. Increasing $\sigma_u$ flattens the LF (and moves it upwards), which is illustrated by the model LFs shown as the solid lines, for which we used $(\langle T_\alpha \rangle, \sigma_u) = (0.27, 0.2)$ (shown as the thick black dot in the inset). The best-fitting model to the data has $\sigma_u \sim 0$ (which corresponds to the model shown in Fig. 2).

Figure 4. Comparison of the observed EW distribution (histogram), with the model prediction for a model in which we assumed a lognormal distribution of IGM transmission with a mean of log $T_{\alpha,57}$ and standard deviation of (in the log) $\sigma_u$ (see the text). This reflects the possibility that the IGM transmission fluctuates between galaxies. The inset shows likelihood contours for $(\langle T_\alpha \rangle, \sigma_u)$. Increasing $\sigma_u$ flattens the LF (and moves it upwards), which is illustrated by the model LFs shown as the solid lines, for which we used $(\langle T_\alpha \rangle, \sigma_u) = (0.27, 0.2)$ (shown as the thick black dot in the inset). The best-fitting model to the data has $\sigma_u \sim 0$ (which corresponds to the model shown in Fig. 2).

Figure 4. Comparison of the observed EW distribution (histogram), with the model prediction for a model in which we assumed a lognormal distribution of IGM transmission with $(\langle T_\alpha \rangle, \sigma_u) = (0.27, 0.2)$ (see Fig. 3). The EW is related to $T_\alpha$ via $\text{EW} = 160 T_\alpha \text{ Å}$. The dotted line shows the fraction $f(> T_\alpha)$ (shown on the right-hand vertical axis), of galaxies with a transmission greater than $T_\alpha$ (equation 5). Galaxies with large $T_\alpha$ are more easily detected, hence the large-$T_\alpha$ (EW) end is boosted considerably, resulting in closer agreement (though not close enough) to the data.
5 Lyα EMITTERS POWERED BY VERY MASSIVE STARS

In Section 3, we demonstrated that a simple model where \( L_\text{UV} \) and \( L_\text{Ly} \) were linearly related to halo mass can reproduce the UV and Ly\( \alpha \) LFs, but not the observed EW distribution. In Section 4, we showed that this situation is not remedied by a variable IGM transmission, and that favoured models have a constant transmission. In this section, we discuss an alternate model, which leads to consistency with the UV and Ly\( \alpha \) LFs, and the EW distribution. In this model, galaxies are assumed to have a bright Ly\( \alpha \) phase (hereafter the ‘Population III phase’) which lasts a fraction \( f_{\text{II}} \) of the galaxy’s lifetime. After this the galaxy’s Ly\( \alpha \) luminosity drops to the ‘normal’ value for Population II star formation.

This model may be viewed as an extension of the idea originally described by Malhotra & Rhoads (2002), that large-EW LAEs are young galaxies in the early stages of their lives. In this picture, the sudden drop in Ly\( \alpha \) luminosity could represent (i) a sudden drop in the ionizing luminosity when the first O-stars died, or (ii) an enhanced dust-opacity after enrichment by the first Type II supernovae. Alternatively, our parametrization could represent a scenario in which the Population III phase ended after the first Population III stars enriched the surrounding interstellar gas from which subsequent generations of stars formed. Hence, we refer to this model as the ‘Population III’ model. We will show that to be consistent with the large values of the observed EW, a very massive population of stars is required during the early stages of star formation.

To minimize the number of free parameters, we modelled the time dependence of the Ly\( \alpha \) EW as a step-function. The number density of LAEs is then given by

\[
N(>T_\alpha \times L_\alpha, z) = f_{\text{II}} \times \epsilon_{\text{DC}} \int_{M_{\text{III}}}^{\infty} \frac{dM}{dM} \left( z \right) \left[ 1 - \frac{f_{\text{II}}}{\epsilon_{\text{DC}}} \int_{M_{\text{III}}}^{\infty} \frac{dM}{dM} \left( z \right) \right].
\]

Here, \( M_{\text{III}} \) is the mass related to \( T_\alpha \times L_\alpha \) through \( T_\alpha \times L_\alpha = L_{\alpha} \times T_\alpha \times M_\alpha \), while \( M_{\epsilon_{\text{DC}}} \) is the Population III mass, which is calculated with \( L_{\alpha} \) replaced by \( L_{\alpha} = (\text{EW}_{\text{III}}/160 \text{ Å}) \times 2 \times 10^{42} \text{ erg s}^{-1} \).

Whereas in previous sections we chose fiducial or best-fitting parameters for illustration, for the model described in this section we take the most general approach. We fit the model simultaneously to the UV LF and Ly\( \alpha \) LFs, as well as to the observed EW distribution of Ly\( \alpha \)-selected galaxies. This model predicts two observed EWs (\( T_\alpha \times \text{EW}_{\text{III}} \) and \( T_\alpha \times \text{EW}_{\text{II}} \)) in various abundances. The associated mean and variance from the model are compared to the observed EW distribution, which has a mean of \( \text{EW} = 120 \pm 25 \text{ Å} \), and a standard deviation of \( \sigma_{\text{EW}} = 50 \pm 10 \text{ Å} \).

Our model has six free parameters (\( \epsilon_{\text{DC}}, f_{\text{II}}, T_{\alpha,57}, T_{\alpha,65}, \text{EW}_{\text{III}} \)). We produce likelihoods for each parameter by marginalizing over the others in this space. The lower set of panels in Fig. 5 show likelihood contours for our model parameters at 64, 26 and 10 per cent of the peak likelihood. The best-fitting models have \( \text{EW}_{\text{III}} \sim 600-800 \text{ Å} \) and \( f_{\text{II}} = 0.05-0.1 \) which corresponds to a physical time-scale for the Population III phase of \( f_{\text{II}} \times \epsilon_{\text{DC}} \times t_{\text{bary}} \sim 4-50 \text{ Myr} \) for \( 0.1 \leq \epsilon_{\text{DC}} \leq 0.5 \). The model Ly\( \alpha \) LFs at \( z = 5.74 \) and 6.5 described by \( \epsilon_{\text{DC}}, f_{\text{II}}, T_{\alpha,57}, T_{\alpha,65}, \text{EW}_{\text{III}} \) is \( (0.2, 0.14, 0.22, 0.19, 0.08, 650 \text{ Å}) \) are shown as the solid lines and provide good fits to the data. The model produces two observed EWs, namely \( T_\alpha \times \text{EW}_{\text{III}} = 35 \text{ Å} \) and \( T_\alpha \times \text{EW}_{\text{II}} = 143 \text{ Å} \).

It is worth emphasizing that the emitted EW of the bright phase depends on the choice \( L_{\alpha,42} \) via \( \text{EW}_{\text{III}} \sim (650 L_{\alpha,42}/2.0) \text{ Å} \). Hence, a lower/higher value of \( L_{\alpha,42} \) would decrease/increase the intrinsic brightness of the ‘Population III’ phase. Note that \( L_{\alpha,42} = 1.0 \) when LAEs formed out of gas of solar metallicity, which is unreasonable, given the Universe was only \( \sim 1 \text{ Gyr} \) old at \( z = 6 \). Furthermore, \( L_{\alpha,42} = 1 \) would have yielded a best-fitting \( T_{\alpha,57} = 0.5 \), which is well outside the range calculated by Dijkstra et al. (2007a). We there conclude that \( L_{\alpha,42} \) is in excess of unity.

In performing fits we have fixed the value of \( \text{EW}_{\text{III}} \) to correspond to a standard stellar population, and then explored the possibility that there might be a second phase of star formation producing a larger EW. Our modelling finds strong statistical evidence for this early phase and rules out the null-hypothesis that properties can be described by Population II stars alone at high confidence (grey region in the lower left-hand panel inset of Fig. 5). Despite the fact that the best-fitting model has a bright phase which lasts only a few per cent of the total star formation lifetime, the two populations of LAEs are similarly abundant in model realizations of the observed sample in Ly\( \alpha \)-selected galaxies (see Section 5.1 for a more detailed comparison to the observed EW distributions). This is shown in the lower left-hand panel in Fig. 5 in which the solid line (with label ‘1.0’) shows the combination of \( f_{\text{II}} \) and \( \text{EW}_{\text{III}} \) for which the observed number of galaxies in the Population III phase (\( N_{\text{III}} \)) equals that in the Population II phase (\( N_{\text{II}} \)). The dashed lines show the cases \( N_{\text{III}}/N_{\text{II}} = 0.3 \) and \( N_{\text{III}}/N_{\text{II}} = 3.0 \). The duration of the bright Ly\( \alpha \) phase meets theoretical expectations for a burst of star formation, while the large EW requires a very massive stellar population (e.g. Schaerer 2003; Tumlinson, Shull & Venkatesan 2003).

In summary, in order to reproduce both the UV and Ly\( \alpha \) LFs, and the observed population of large-EW galaxies, we require a burst of very massive star formation lasting \( \lesssim 10 \) per cent of the galaxy’s lifetime.

5.1 EW distribution of UV- and Ly\( \alpha \)-selected galaxies

Stanway et al. (2007) show that 11 out of 14 LAE candidates among i-drop galaxies in the Hubble Ultra Deep Field (HUDF) have EW \( < 100 \text{ Å} \). If galaxies are included for which only upper or lower limits on the EW are available, then this fraction becomes 21 out of 26. Thus, the distribution of EWs for i-drop selected galaxies differs strongly from the EW distribution observed by Shimasaku et al. (2006). We next describe why this strong dependence of the observed Ly\( \alpha \) EW distribution on the precise galaxy selection criteria arises naturally in our Population III model.

We first assume that the Ly\( \alpha \)-selected and UV-selected galaxies were drawn from the same population (this assumption is discussed
formation to be observed in the Population III model. Note that our model predicts Population III star formation in a large number of high-redshift LAEs.

Further in Section 6.3. In our model a galaxy that is selected based on its rest-frame UV-continuum emission has a probability \( f_\text{III} \) of being observed in the \( \text{Ly}\alpha \) bright phase, while the probability of finding galaxies in the \( \text{Ly}\alpha \) faint phase is \( 1 - f_\text{III} \). In Section 5, we found \( f_\text{III} \sim 0.1 \); hence, an i-drop galaxy is \( \sim 10 \) times more likely to have a low than a high observed EW. If we denote the number of galaxies with \( \text{EW} > 100 \text{Å} \) by \( N_\text{III} \), and the number of galaxies with \( \text{EW} < 100 \text{Å} \) by \( N_\alpha \), then the model predicts \( N_\text{III}/N_\alpha = f_\text{III}/(1 - f_\text{III}) \sim 0.1 \), while the observed fraction including the galaxies for which the EW is known as upper or lower limit is \( N_\text{III}/N_\alpha = 0.19 \pm 0.05 \). Therefore, the qualitative difference in observed \( \text{Ly}\alpha \) EW distribution among i-drop galaxies in the HUDF and among \( \text{Ly}\alpha \)-selected galaxies follows naturally from our two-phase star formation model. Note that our model predicts Population III star formation to be observed in \( f_\text{III}/(1 - f_\text{III}) \sim 10 \) per cent of the \( z = 6.0 \) LBG population.

The dependence of the observed EW distribution on the selection criteria used to construct the sample of galaxies is illustrated in Fig. 6. To construct this figure, we have taken the best-fitting Population III model of Section 5. For the purpose of presentation, we let the IGM fluctuate according to the prescription of Section 4 with \( \sigma_\alpha = 0.1 \), so that the model predicts a finite range of EWs in each phase. The left- and right-hand panels show the predicted EW distribution for \( \text{Ly}\alpha \)-selected (left-hand panel) and UV-selected (right-hand panel) galaxies as the solid lines, respectively. For a UV-selected galaxy the probability of being in the bright phase and having an observed EW in the range \( \text{EW}_\text{III} \times (T_\alpha \pm dT_\alpha/2) \) is \( f_\text{III} P(T_\alpha)dT_\alpha \). Here \( P(T_\alpha)dT_\alpha \) is the probability that the IGM transmission is in the range \( T_\alpha \pm dT_\alpha/2 \), which is derived from equation (4). The units on the vertical axis are arbitrary, and chosen to illustrate the different predicted and observed \( \text{Ly}\alpha \) EW distributions for the two samples at large EWs. The observed distributions for \( \text{Ly}\alpha \)- and UV-selected galaxies, shown as the histograms, are taken from Shimakatu et al. (2006) and Stanway et al. (2007), respectively. Fig. 6 clearly shows that both the predicted and observed \( \text{Ly}\alpha \)-selected samples contain significantly more large-EW
LAEs than the UV-selected sample. Our model naturally explains the qualitative shape of these distributions and their differences.

Before proceeding we mention a caveat to the distributions shown in Fig. 6. In our model all galaxies have an EW of $\mathcal{T}_\alpha \times \text{EW}_{\text{II}} \sim 25$–35 Å during the Population II phase, while in contrast Stanway et al. (2007) do not detect 10 out of 26 LBGs, which implies that $\sim$40 per cent of LBGs have an EW $\lesssim 6$ Å. Thus, there is a discrepancy between our model and the observations with respect to the value of EW in the Population II phase. The resolution of this discrepancy lies in the fact that the very low EW emitters are drawn from the UV (i-drop) sample and not the Lyo-selected sample our model was set up to describe. This issue is discussed in more detail in Section 6.3.

An EW distribution of dropout sources was also presented by Dow-Hygelund et al. (2007). These authors performed an analysis similar to Stanway et al. (2007) and found one LAE with EW = 150 Å among 22 candidate $z = 6.0$ LBGs. When interpreted in reference to our model, this translates to $N_{\text{II}}/N_{\text{II}} \sim 5$ per cent, which is consistent with the model predictions. Therefore, when interpreted in light of a two-phase star formation history and different selection methods, the EW distribution observed by Dow-Hygelund et al. (2007) is consistent with that found by Shimasaku et al. (2006).

If Population III star formation does provide the explanation for the very large EW Ly$\alpha$ emitters, then we would expect the large-EW emitters to become less common with time as the mean metallicity of the Universe increased. To test this idea, we can compare the EW distribution at $z = 5.7$ with the results at lower redshift from Shapley et al. (2003) who found that $\lesssim 0.5$ per cent of $z = 3$ LBGs have Ly$\alpha$ EW $\gtrsim 150$ Å, and that $\lesssim 2$ per cent of $z = 3$ LBGs have Ly$\alpha$ EW $\gtrsim 100$ Å. Dow-Hygelund et al. (2007) argue that the fraction of large-EW Ly$\alpha$ lines at $z = 6$ is consistent with that observed at $z = 3$ (Shapley et al. 2003). However, if the EW distribution did not evolve with redshift, then the probability that a sample of 22 LBGs will contain at least one LAE with EW $\gtrsim 150$ Å is $\lesssim 10$ per cent. Thus, the hypothesis that the observed EW distribution remains constant is ruled out at the $\sim$90 per cent level. On the other hand, in a similar analysis Stanway et al. (2007) found five out of 26 LBGs to have an EW $\gtrsim 100$ Å. If the EW distribution did not evolve with redshift, then the probability of finding five EW $\gtrsim 100$ Å in this sample is only $\sim 10^{-4}$. Furthermore, Nagao et al. (2007) recently found at least five LBGs with EW $\gtrsim 100$ Å at 6.0 $\lesssim z \lesssim 6.5$, and conclude that 8 per cent of i’-drop galaxies in the Subaru Deep Field have EW $\gtrsim 100$ Å, which is significantly larger than the fraction of large-EW LBGs at $z = 3$. Therefore, the observed EW distribution of LBGs at $z = 6$ is skewed more towards large EWs than at $z = 3$. The strength of this result is increased by the fact that the IGM is more opaque to Ly$\alpha$ photons at $z = 6$ than at $z = 3$. Thus, we conclude that the intrinsic EW distribution must have evolved with redshift.

6 DISCUSSION

6.1 Comparison with population-synthesis models

Population-synthesis models have suggested that the broad-band colours of observed LAEs are best described with young stellar populations (Gawiser et al. 2006; Pirzkal et al. 2007; Finkelstein et al. 2007). Lai et al. (2007) found the stellar populations in three LAEs to be 5–100 Myr old, and possibly as old as 700 Myr (where the precise age upper limit depends on the assumed star formation history of the galaxies). However, as was argued by Pirzkal et al. (2007), since these galaxies were selected based on their detection in IRAC, a selection bias towards older stellar populations may exist (also see Lai et al. 2007). Furthermore, Finkelstein et al. (2007) found that LAEs with EW $\gtrsim 10$ Å have ages $\lesssim 4$ Myr, while LAEs with EW $< 40$ Å have ages between 20 and 400 Myr. This latter result in particular agrees well with our Population III model. On the other hand, in a fluctuating IGM model, for example, the EW of LAEs should be uncorrelated with age.

In models presented in this paper, on average $f_\alpha \sim 0.15$ of all baryons is converted into stars within haloes of mass $M_{\text{tot}} \sim 10^{10}$–$10^{11}$ M$\odot$, yielding stellar masses in the range $M_* = 10^{10}$–$10^{11}$ M$\odot$ (Dijkstra et al. 2007b; Stark et al. 2007). This compares unfavourably with the typical stellar masses found observationally in LAEs which can be as low as $M_* = 10^9$–$10^{10}$ M$\odot$ (Finkelstein et al. 2007; Pirzkal et al. 2007). However, the lowest stellar masses are found (naturally) for the younger galaxies. Indeed, the LAEs with the oldest stellar populations can have stellar masses as large as $10^{10}$ M$\odot$. Thus, we do not find the derived stellar masses in LAEs to be at odds with the results of this paper. If significant very massive (or Population III) star formation indeed occurred in high-redshift LAEs, then one may expect these stars to reveal themselves in unusual broad-band colours (e.g. Stanway, McMahon & Bunker 2005).

However, Tumlinson et al. (2003) have shown that the most distinctive feature in the spectrum of Population III stars is the number of H and He ionizing photons (also see Bromm et al. 2001). Since these are (mostly) absorbed in the IGM, the broad-band spectrum of Population III stars is in practice difficult to distinguish from a normal stellar population (Tumlinson et al. 2003), especially when nebular continuum emission is taken into account (Schaerer & Pelló 2005, see their fig. 1). Hence, Population III stars would not necessarily be accompanied by unusually blue broad-band colours.

6.2 Alternative explanations for large-EW LAEs

We have shown that a simple model in which high-redshift galaxies go through a Population III phase lasting $\lesssim 15$ Myr can simultaneously explain the observed Ly$\alpha$ LFs at $z = 5.7$ and 6.5 (Kashikawa et al. 2006), and the observed EW distribution of Ly$\alpha$-selected galaxies at $z = 5.7$ (Shimasaku et al. 2006). In addition, this model predicts the much lower EWs found in the population of UV-selected galaxies (Stanway et al. 2007, see Section 5.1). Moreover, the constraints on the Population III model parameters such as the duration and the EW of the bright phase are physically plausible, and consistent with existing population-synthesis work (see Section 6.1).

Are there other interpretations of the large observed EWs? One possibility was discussed in Section 4, where we showed that the simple model in which the IGM transmission fluctuates between galaxies reproduces the LFs, but fails to simultaneously reproduce the Ly$\alpha$ LFs and the observed EW distribution. In addition, this model fails to reproduce other observations. Dijkstra et al. (2007a) calculated the impact of the high-redshift reionized IGM on Ly$\alpha$ emission lines and found the range of plausible transmissions to lie in the range 0.1 $< \mathcal{T}_\alpha < 0.3$. This work showed that it is possible to boost the transmission to (much) larger values but without increasing the observed width of the Ly$\alpha$ line. Absorption in the IGM typically erases all flux bluewards of the Ly$\alpha$ resonance, and when infall is accounted for, part of the Ly$\alpha$ redwards of the Ly$\alpha$ resonance as well. This implies that Ly$\alpha$ lines that are affected by absorption in the IGM are systematically narrower than they would have been if no absorption in the IGM had taken place. It follows that in the fluctuating IGM model, Ly$\alpha$ EW should be strongly correlated with the observed Ly$\alpha$ line-width (or FHWM). This correlation is not observed. In fact, observations suggest that an anticorrelation exists.
between EW and full width at half-maximum (FWHM) (Shimasaku et al. 2006; Tapken et al. 2007). This anticorrelation provides strong evidence against the anomalously large EWs being produced by a fluctuating IGM transmission.

A second possibility is the presence of galaxies with strong superwinds. The models of Dijkstra et al. (2007a) did not study the impact of superwinds on the Lyα line profile. The presence of superwinds can cause the Lyα line to emerge with a systematic redshift relative to the Lyα resonance through back scattering of Lyα photons off the far side of the shell that surrounds the galaxy (Ahn, Lee & Lee 2003; Ahn 2004; Hansen & Oh 2006; Verhamme, Schaerer & Maselli 2006). However, superwinds tend not only to redshift the Lyα line, but also to make the Lyα line appear broader than when this scattering does not occur. As in the case of the fluctuating IGM model, this results in a predicted correlation between EW and v_{FWHM}, when this scattering does not occur. As in the case of the Lyα line, but also to make the Lyα line appear broader than when this scattering does not occur. As in the case of the fluctuating IGM model, this results in a predicted correlation between EW and v_{FWHM}, when this scattering does not occur.

3 LBGs by Shapley et al. (2003) show that EW correlates with v_{FWHM}, and thus T_{v}, increases with wind velocity, v_{w}. This predicts that EW increases with wind velocity. However, observations of z = 3 LBGs by Shapley et al. (2003) show that EW correlates with v_{w}^{-1} (Ferrara & Ricotti 2006). We therefore conclude that the large EW in LAEs cannot be produced by superwind galaxies.

A third possibility might be that within the LAE, cold, dusty clouds lie embedded in a hot intercloud medium of negligible Lyα opacity. Under such conditions, the continuum photons can suffer more attenuation than Lyα photons which bounce from cloud to cloud and mainly propagate through the hot, transparent intercloud medium (Neufeld 1991; Hansen & Oh 2006). This attenuation of continuum leads to a large EW. We point out that in this scenario, large-EW LAEs are not intrinsically brighter in Lyα. At fixed Lyα flux, one is therefore equally likely to detect a low-EW LAE. In other words, to produce the observed EW distribution one requires preferential destruction of continuum flux by dust in ~50 per cent of the galaxies. Currently, there is no evidence that this mechanism is at work even in one galaxy. Furthermore, the rest-frame UV colours of galaxies in the HUFD imply that dust in high-redshift galaxies suppresses the continuum flux by only a factor of ~1.4 (Bouwens et al. 2006). The maximum boost of the EW in a multiphase ISM is therefore 1.4, which is not nearly enough to produce intrinsic EWs of ~600–800 Å. In summary, the only model able to simultaneously explain all observations calls for a short burst of very massive star formation.

### 6.3 Comparison with the LBG population

In Section 5.1, we have shown that the observed EW distributions of Lyα-selected and i-drop galaxies and their differences can be reproduced qualitatively with our Population III model. However, in our model all high-redshift galaxies have an observed EW of at least T_{v} × EW_{i} ~ 30 Å, whereas many i-drop galaxies are not detected in Lyα. Kashikawa et al. (2006) show that the UV LFs of LAEs at z = 6.5 and 5.7 overlap with that constructed by Bouwens et al. (2006) from a sample of ~300 z = 6 LBGs discovered in the Hubble Deep Fields. Naively, this overlap implies that LBGS and LAEs are the same population and therefore that all LBGs should be detected by i-drop surveys. Since Lyα surveys only detect galaxies with EW ~ 20 Å, this suggests that all LBGs should have a Lyα EW ~ 20 Å contrary to observation. To illustrate this point further, we have taken the best-fitting Population III model shown in Fig. 5 and compared the model predictions for the rest-frame UV LF with that described by Bouwens et al. (2006) in Fig. 7. Clearly, our best-fitting Population III model fits the data well. However, Stanway et al. (2007) found ~40 per cent of i-drop galaxies in the HUDF to have an observed EW ~ 6 Å, and a similar result was presented by Dow-Hygelund et al. (2007).

Two effects may help reconcile these two apparently conflicting sets of observations: (i) Dow-Hygelund et al. (2007) found Lyα-emitting LBGs to be systematically smaller, that is, for a fixed angular size, the z_{500}-band flux of LAEs is systematically higher with ∆z_{500} ~ −1. If we assume that the angular scale of a galaxy is determined by the mass of its host halo, then this implies that for a fixed mass the z_{500}-band flux of LAEs is systematically higher, and (ii) only a fraction of LBGs are LAEs. The drop-out technique used to select high-redshift galaxies is known to introduce a bias against strong LAEs, as a strong Lyα line can affect the broad-band colours of high-redshift galaxies. This may cause ~10–46 per cent of large-EW LAEs to be missed using the i-drop technique (Dow-Hygelund et al. 2007).

If only a fraction f_{w} of all LBGs are detected in Lyα, then effect (i) would explain why the UV LF of LAEs lies less than a factor of 1/f_{w} below the observed UV LF of the general population of LBGs. This is because a more abundant lower mass halo is required to produce the same UV flux in LAEs, which would shift the LF upwards. In addition, effect (ii) may reduce this difference even further. It follows that these two effects combined may cause the LF to overlap. Thus, the overlap of the UV- and Lyα-emitting LF appears to be a coincidence, and not evidence of their being the same population of galaxies. This implies that our model is valid for Lyα-emitting galaxies, but not the high-redshift population as a whole, and explains the lack of very low EWs in UV-selected samples discussed in Section 5.1.

The reason why LAEs may be brighter in the UV for a fixed halo mass is unclear. It is possibly related to dust content. Bouwens et al. (2006) found the average amount of UV extinction to be 0.4 mag in the total sample of z = 6 LBGs. This value is close to the average excess z_{500}-band flux detected from LAEs for a given angular scale (Dow-Hygelund et al. 2007). If LAEs contain less (or no) dust, then this would explain why they are brighter in the UV and thus why they appear more compact. The possibility that ‘Lyα-quiet’ LBGs...
contain more dust than their Lyα-emitting counterparts is not very surprising, as a low dust abundance has the potential to eliminate the Lyα line. Thus, LAEs could be high-redshift galaxies with a lower dust content.

Shimasaku et al. (2006) and Ando et al. (2006) found that luminous LBGs, $M_{UV} \lesssim -21.0$, typically do not contain large-EW Lyα emission lines. This deficiency of large-EW LAEs among UV-bright sources is not expected in our model, and may reflect that UV-bright sources are more massive, mature, galaxies that cannot go through a Population III phase anymore. It should be pointed out though that the absence of large-EW LAEs among galaxies with $M_{UV} \lesssim -21.0$ in the survey of Shimasaku et al. (2006) is consistent with our model: the observed number density of sources with $M_{UV} \lesssim -21.0$ is $\sim 5 \times 10^{-3}$ cMpc$^{-3}$ (see Fig. 1). In our best-fitting Population III model (shown in Fig. 5), a fraction $f_{HI} \sim 0.08$ of these galaxies would be in the bright phase. This translates to a number density of large-EW LAEs of $\sim 4 \times 10^{-6}$ cMpc$^{-3}$. Given the survey volume of $\sim 2 \times 10^{5}$ cMpc$^{3}$, the expected number of large-EW LAEs with $M_{UV} \lesssim -21.0$ is $\sim 0.8$, and the absence of large-EW LAE among UV bright sources is thus not surprising.

6.4 Clustering properties of the LAEs

In our model large-EW LAEs are less massive by a factor of $EW_{HI}/EW_{UV} \sim 4$ at fixed Lyα luminosity. Since clustering of dark matter haloes increases with mass, it follows that our model predicts large-EW LAEs to be clustered less than their low-EW counterparts (at a fixed Lyα luminosity). The clustering of LAEs is typically quantified by their angular correlation function (ACF), $w(\theta)$, which gives the excess (over random) probability of finding a pair of LAEs separated by an angle $\theta$ on the sky. The ACF depends on the square of the bias parameter $[w(\theta) \propto b^{2}(m)]$, which for galaxies in the Population II phase is $\sim 1.24$–1.4 times larger than for galaxies in the Population III phase, for the mass range of interest. This implies that the clustering of low-EW LAEs at fixed Lyα luminosity is enhanced by a factor of $\sim 1.5$–2.0. Existing determinations of the ACF of LAEs by Shimasaku et al. (2006) and Kashikawa et al. (2006) are still too uncertain to test this prediction.

7 CONCLUSIONS

Observations of high-redshift LAEs have shown the typical EW of the Lyα line to increase dramatically with redshift, with a significant fraction of the galaxies lying at $z \gtrsim 5.7$ having an EW $\gtrsim 100$ Å. Recent calculations by Dijkstra et al. (2007a) show that the IGM at $z \gtrsim 4.5$ transmits only 10–30 per cent of the Lyα photons emitted by galaxies. In this paper, we have investigated the transmission using a model that reproduces the observed Lyα and UV LFs. This model results in an empirically determined transmission of $T_{\alpha} \sim 0.30(L_{UV,32}/2.0)^{-1}$, where $L_{UV,32}$ denotes the Lyα luminosity per unit star formation rate (in M$_{\odot}$ yr$^{-1}$) $L_{\alpha}$ in units of 10$^{42}$ erg s$^{-1}$ (Section 3). This value is in good agreement with earlier theoretical results.

If only $\sim 30$ per cent of all Lyα that was emitted by high-redshift galaxies reaches the observer, then this implies that the intrinsic EWs are systematically (much) larger than that observed in many cases. To investigate the origin of these very high EWs, we have developed semi-analytic models for the Lyα and UV LFs and the distribution of EWs. In this model Lyα emitters undergo a burst of very massive star formation that results in a large intrinsic EW, followed by a phase of Population II star formation that produces a lower EW. This model is referred to as the ‘Population III model’ and is an extension of the idea originally described by Malhotra & Rhoads (2002), who proposed large-EW Lyα emitters to be young galaxies.

The Population III model in which the Lyα EW is $EW_{\alpha} \sim 650(L_{UV,32}/2.0)$ Å for $z \lesssim 50$ Myr is able to simultaneously describe the following eight properties of the high-redshift galaxy population: (i)–(iv) the UV and Lyα LFs of LAEs at $z = 5.7$ and 6.5, (v)–(vi) the mean and variance of the EW distribution of Lyα-selected galaxies at $z = 5.7$, (vii) the EW distribution of UV-selected galaxies at $z \sim 6$ (Section 5), and (viii) the observed correlation of stellar age and mass with EW (Section 6.1). Our modelling suggests that the anomalously large intrinsic EWs observed in about half of the high-redshift Lyα emitters require a burst of very massive star formation lasting no more than a few to 10 per cent of the galaxy’s star-forming lifetime. This very massive star formation may indicate the presence of Population III star formation in a large number of high-redshift LAEs. The model parameters for the best-fitting model are physically plausible where not previously known (e.g. those related to the efficiency and duration of star formation), and agree with estimates where those have been calculated directly (e.g. the IGM transmission, $EW_{HI}$, and $f_{HI}$).

In addition, we argued that the observed overlap of the UV LFs of LAEs with that of $z \sim 6$ LBGs appears to be at odds with the observed Lyα detection rate in high-redshift LBGs, suggesting that LAEs and LBGs are not the same population. A lower dust content of LAEs relative to their ‘Lyα-quiet’ counterparts would partly remedy this discrepancy, and could also explain why LAEs appear to be typically more compact (Section 6.3).

Semi-analytic modelling of the coupled reionization and star formation histories of the Universe suggests that Population III star formation could still occur after the bulk of reionization had been completed (Scannapieco, Schneider & Ferrara 2003; Schneider et al. 2006; Wyithe & Cen 2007). The observation of anomalously large EWs in LAEs at high redshift may therefore provide observational evidence for such a scenario. In the future, the He 1640 Å line may be used as a complementary probe (e.g. Tumlinson, Giroux & Shull 2001; Tumlinson et al. 2003). The EW of this line is smaller by a factor of $\gtrsim 20$ for Population III (Schaerer 2003). However, the He 1640 Å line will not be subject to a small transmission of $\sim 10$–30 per cent, making it accessible to the next generation of space telescopes. On the other hand, it may also be possible to observe the He 1640 Å line in a composite spectrum of $z = 6$ LBGs. Indeed, the He 1640 Å line has already been observed in the composite spectrum of $z = 3$ LBGs (Shapley et al. 2003), which led Jimenez & Haiman (2006) to argue for Population III star formation at redshifts as low as $z = 3$. If Population III star formation was more widespread at higher redshifts, as predicted by our model, then the composite spectrum of LBGs at higher redshifts should exhibit an increasingly prominent He 1640 Å line. In particular, this line should be most prominent in the subset of LBGs that have large-EW Lyα emission lines.

3 Technically, the model discussed in Section 5 only specifies that galaxies go through a ‘Population III’ phase for a fraction $f_{HI} \sim 0.1$ of their lifetimes. Our model does not specify when this Population III phase occurs. Hypothetically, the Population III phase could occur at an arbitrary moment in the galaxy’s lifetime when it is triggered by a merger of a regular star-forming galaxy and a dark matter halo containing gas of primordial composition. Note, however, that such a model would probably have difficulties explaining the apparent observed correlation between Lyα EW and the age of a stellar population (Section 6.1).
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