The visibility of Lyman α emitters: constraining reionization, ionizing photon escape fractions and dust

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ABSTRACT
We build a physical model for high-redshift Lyman α emitters (LAEs) by coupling state-of-the-art cosmological simulations (GADGET-2) with a dust model and a radiative transfer code (PCRASH). We post-process the cosmological simulation with PCRASH using five different values of the escape fraction of hydrogen ionizing photons ($f_{\text{esc}} = 0.05, 0.25, 0.5, 0.75, 0.95$) until reionization is complete, i.e. the average neutral hydrogen fraction drops to $\langle \chi_{\text{HI}} \rangle \approx 10^{-4}$. Then, the only free parameter left to match model results to the observed Lyα and UV luminosity functions of LAEs at $z \approx 6.6$ is the relative escape of Lyman α and continuum photons from the galactic environment ($f_\alpha / f_c$). We find a three-dimensional degeneracy such that the theoretical model can be reconciled with observations for an intergalactic medium Lyα transmission ($T_\alpha \approx 38–50$ per cent (which translates to $\langle \chi_{\text{HI}} \rangle \approx 0.5–10^{-4}$ for Gaussian emission lines), $f_{\text{esc}} \approx 0.05–0.50$ and $f_\alpha / f_c \approx 0.6–1.8$.

Key words: radiative transfer – methods: numerical – dust, extinction – galaxies: high-redshift – dark ages, reionization, first stars.

1 INTRODUCTION

The epoch of reionization (EoR) begins when the first stars start producing neutral hydrogen (H i) ionizing photons, carving out an ionized Strömgren region in the neutral intergalactic medium (IGM) around themselves, and ends when all the H i in the IGM is ionized. Understanding the process of cosmic reionization is extremely important because in addition to marking the last major change in the ionization state of the Universe, it affected all subsequent structure formation through a number of radiative feedback effects (see e.g. Barkana & Loeb 2001; Ciardi & Ferrara 2005; Maio et al. 2011; Sobacchi & Mesinger 2013; Wyithe & Loeb 2013, and references therein). A broad picture that has emerged (Choudhury & Ferrara 2007) is one wherein hydrogen reionization is an extended process that starts at $z \approx 15$ and is about 90 per cent complete by $z \approx 8$; while it is initially driven by metal-free Population III stars in low-mass haloes ($\leq 10^8 M_\odot$), the conditions for star formation (SF) in these haloes are soon erased by a combination of chemical and radiative feedback by $z \approx 10$. However, any attempt at modelling reionization necessarily requires a number of important assumptions regarding the number of H i ionizing photons produced by the source galaxy population depending on their physical properties, the fraction of these photons ($f_{\text{esc}}$) that can escape out of the galactic environment and contribute to reionization, and the clumping factor of the IGM at high redshifts, to name a few (Salvaterra, Ferrara & Dayal 2011). Given these assumptions, reionization scenarios need to be constantly updated as new data sets are acquired.

By virtue of their continually growing numbers, a valuable new data set is provided by high-redshift Lyman α emitters (LAEs); this is a class of galaxies identified by means of their Lyman α (Lyα) emission line at 1216 Å in the galaxy rest frame. Indeed, hundreds of LAEs have now been confirmed in the EoR: $z \approx 5.7$ (Malhotra et al. 2005; Shimasaku et al. 2006; H. et al. 2010; Curtis-Lake et al. 2012), $z \approx 6.6$ (Taniguchi et al. 2005; Kashikawa et al. 2006, 2011; Hu et al. 2010; Ouchi et al. 2010) and $z \approx 7$ (Iye et al. 2006; Ouchi et al. 2009; Stark et al. 2010; Pentericci et al. 2011). In addition to their number statistics, LAEs have been rapidly gaining popularity as probes of reionization and high-redshift galaxy evolution for two reasons: (a) the strength, width and continuum break bluewards of the Lyα line make their detection unambiguous, and (b) Lyα photons are extremely sensitive to attenuation by H i; the observed Lyα luminosity can then be used to infer the ionization state of the IGM at redshifts close to those of the emitter and hence to reconstruct, at least piecewise, the cosmic reionization history.

However, interpreting LAE data is complicated by a number of physical effects. First, the intrinsic Lyα luminosity depends on the total number of H i ionizing photons that are produced by a galaxy, depending on the star formation rate (SFR), age and metallicity of its stellar population (e.g. Santos 2004). Secondly, depending on the H i and dust contents in the interstellar medium (ISM), only a fraction ($1 - f_{\text{esc}}$) of these H i ionizing photons are able to contribute to the intrinsic Lyα luminosity by ionizing the ISM H i;
the rest contribute to building the ionized H II region around the galaxy. We briefly digress to note that the dependence of $f_{\text{esc}}$ on galaxy properties has been the subject of much recent debate: while some authors find $f_{\text{esc}}$ to decrease with an increase in the halo mass (Razoumov & Sommer-Larsen 2010; Yajima, Choi & Nagamine 2011; Ferrara & Loeb 2013), other works find the opposite trend (Gnedin, Kravtsov & Chen 2008; Wise & Cen 2009). The value of $f_{\text{esc}}$ also remains poorly constrained with findings ranging from a few per cent (e.g. Gnedin et al. 2008) up to 20–30 per cent (e.g. Mitr, Ferrara & Choudhury 2013) or even higher (e.g. Wise & Cen 2009).

Thirdly, only a fraction ($f_\alpha$) of the Ly$\alpha$ photons produced inside a galaxy can escape out of it unattenuated by dust (Dayal, Ferrara & Gallant 2008; Finkelstein et al. 2009; Nagamine et al. 2010; Forero-Romero et al. 2011; Dayal & Ferrara 2012). Fourthly, only a fraction ($T_u$) of the Ly$\alpha$ photons that emerge out of a galaxy are transmitted through the IGM and reach the observer. As expected, this transmission sensitively depends on the IGM H ionization state and it has been shown that only galaxies residing in overlapping H II regions would be observed as LAEs in the initial stages of reionization, i.e. reionization increases the observed clustering of LAEs (McQuinn et al. 2007a; Dayal et al. 2009). Fifthly, the Ly$\alpha$ IGM transmission calculation is complicated by the presence of peculiar velocities. Inflows (outflows) of gas into (from) the emitter blueshift (redshift) the Ly$\alpha$ line, leading to a decrease (increase) in the value of $T_u$ along different lines of sight (LOS), strongly affecting the visibility of galaxies as LAEs (Verhamme, Schaerer & Maselli 2006; Iliev et al. 2008; Zheng et al. 2010; Dijkstra, Mesinger & Wyithe 2011). Indeed, Santos (2004) has shown that the IGM ionization state cannot be constrained in the presence of peculiar velocities. However, Dayal et al. (2011) have shown that the interpretation of LAE data is much more involved; a decrease in the Ly$\alpha$ transmission due to peculiar velocities and/or a highly neutral IGM can be compensated by an increase in $f_\alpha$ due to dust being clumped in the ISM of LAEs, as per the \textquoteleft Neufeld model\textquoteright (Neufeld 1991).

A number of past theoretical works have used one or more of the above ingredients to use LAEs as tracers of reionization. With semi-analytic modelling, a number of authors (e.g. Dijkstra, Lidz & Wyithe 2007; Dayal et al. 2008; Samui, Srianand & Subramanian 2009) have shown that the LAE Ly$\alpha$ luminosity functions (LFs) are consistent with a fully ionized IGM and can be explained solely by an evolution of the underlying dark matter (DM) halo mass functions. However, when considered in combination with the non-evolving ultraviolet (UV) LFs of LAEs between $z \approx 5.7$ and 6.6 (Kashikawa et al. 2006), some of these works (Dijkstra et al. 2007; Ouchi et al. 2010) argue for an additional dimming of the Ly$\alpha$ line by about 30 per cent. A number of studies have used large pure DM simulations to study the clustering of LAEs (McQuinn et al. 2007b; Iliev et al. 2008; Orsi et al. 2008). Finally, a number of studies have been undertaken using cosmological hydrodynamic simulations with dust (Dayal et al. 2008, 2009; Nagamine et al. 2010; Forero-Romero et al. 2011), with radiative transfer (RT) without dust (Zheng et al. 2010) and RT with dust (Dayal et al. 2011; Forero-Romero et al. 2011; Duval et al. 2014).

This work is quite close in spirit to the calculations presented in Dayal et al. (2011) wherein the authors used a (a) cosmological hydrodynamic simulations run with \textsc{gadget-2} to obtain the physical properties of $z \approx 5.7$ galaxies, (b) a dust model that took into account the entire SF history of each galaxy to calculate its dust enrichment and (c) an RT code (\textsc{crash}) to obtain the ionization fields to calculate the IGM Ly$\alpha$ transmission for each galaxy, in order to identify the simulated galaxies that would be observationally classified as LAEs. Using this model, the authors showed that the effects of dust and IGM are degenerate in affecting the visibility of LAEs such that a large $f_\alpha$ can be compensated by a small $T_u$ and vice versa to yield a given value of the observed Ly$\alpha$ luminosity. However, the main caveat in that work was that the authors used a constant value of $f_{\text{esc}} = 0.02$ (Gnedin et al. 2008) for all galaxies in their calculations, and started their RT runs assuming the IGM gas to be in photoionization equilibrium with a uniform ultraviolet background (UVB) produced by unresolved sources corresponding to an average neutral hydrogen fraction, $\langle X_H \rangle = 0.3$.

In this work, we substantially enhance the model presented in Dayal et al. (2011) to build a self-consistent model that couples cosmological smoothed particle hydrodynamic (SPH) simulations, dust modelling and a fast RT code (\textsc{crash}) to identify LAEs without making any prior assumptions on the IGM ionization state, $f_{\text{esc}}$ and the ISM dust distribution. Starting from a uniform neutral IGM, consistent with the Haardt & Madau (1996) background imposed in simulations, we use five different values of $f_{\text{esc}} = 0.05, 0.25, 0.5, 0.75, 0.95$ in order to study how varying $f_{\text{esc}}$ affects the visibility of LAEs through (a) the direct impact on the intrinsic Ly$\alpha$ luminosity, and (b) the IGM Ly$\alpha$ transmission that depends on the topology and extent of H II regions as determined by $f_{\text{esc}}$. Comparing the statistics of the simulated LAEs to observations, our aim is to jointly constrain three fundamental parameters that determine the visibility of LAEs $-f_{\text{esc}}$, $X_H$, and the relative escape of Ly$\alpha$ photons with respect to continuum photons from the dusty ISM of galaxies ($f_\alpha$).

We begin by describing the hydrodynamical simulation, the dust model and the identification of galaxies as Lyman break galaxies (LBGs) through the UV continuum in Section 2. We follow this approach since UV photons are only attenuated by dust but unaffected by the IGM ionization state, simplifying their identification. In order to validate the simulations, we compare the simulated LBG UV LFs to observations in Section 3; a comparison of the simulated LBG stellar mass functions, stellar mass densities (SMDs) and specific star formation rates (sSFRs) with the observations is shown in Appendix A for completeness. Once the physical properties of the simulated galaxies have been validated, we choose a simulation snapshot at the edge of the EoR ($z \approx 6.7$) and post-process it with a fast RT code (\textsc{crash}) with the five values of $f_{\text{esc}}$ mentioned above, as explained in Section 4. We then compare the simulated LAE UV and Ly$\alpha$ LFs with observations (Kashikawa et al. 2011) in Section 5 in order to jointly constrain $f_{\text{esc}}$, $X_H$, and $f_\alpha$. Due to the model-dependent relation between $X_H$ and the IGM transmission ($T_u$), we show our constraints also in terms of $f_{\text{esc}}$, $T_u$ and $f_\alpha$, before concluding in Section 6.

2 COSMOLOGICAL HYDRODYNAMIC SIMULATIONS

In this section, we describe the cosmological simulation used to obtain the physical properties of high-redshift galaxies and the semi-analytic model used to obtain their dust enrichment, in order to calculate their observed visibility in the UV.

2.1 The simulation

The hydrodynamical simulation analysed in this work has been carried out using the TreePM-SPH code \textsc{gadget-2} (Springel 2005). The adopted cosmological model corresponds to the $\Lambda$ cold dark matter universe with dark matter (DM), dark energy and baryonic density parameter values of $(\Omega_\Lambda, \Omega_m, \Omega_b) = (0.73, 0.27, 0.047)$, a Hubble constant $H_0 = 100h = 70 \text{km s}^{-1} \text{Mpc}^{-1}$ and a
normalization $\sigma_z = 0.82$, consistent with the results from the Wilkinson Microwave Anisotropy Probe 5 (Komatsu et al. 2009). The simulation box has a size of 80 $h^{-1}$ comoving Mpc (cMpc), and contains 10243 DM particles, and initially the same number of gas particles; the mass of a DM and gas particle is $3.6 \times 10^6 h^{-1} M_\odot$ and $6.3 \times 10^6 h^{-1} M_\odot$, respectively. The softening length for the gravitational force is taken to be $3 h^{-1}$ comoving kpc and the value of the smoothing length for the SPH kernel for the computation of hydrodynamic forces is allowed to drop at most to the gravitational softening.

The runs include the SF prescriptions of Springel & Hernquist (2003) such that the ISM is described as an ambient hot gas containing cold clouds, which provide the reservoir for SF, with the two phases being in pressure equilibrium; the relative number of stars of different masses is computed using the Salpeter initial mass function (IMF; Salpeter 1955) between 0.1 and 100 $M_\odot$. The density of the cold and of the hot phase represents an average over small regions of the ISM, within which individual molecular clouds cannot be resolved by simulations sampling cosmological volumes. The runs also include the feedback model described in Springel & Hernquist (2003) which includes (a) thermal feedback: supernovae (SN) inject entropy into the ISM, heat up nearby particles and destroy molecules, (b) chemical feedback: metals produced by SF and SN are carried by winds and pollute the ISM, and (c) mechanical feedback: galactic winds powered by SN. In the case of mechanical feedback, the momentum and energy carried away by the winds are calculated assuming that the galactic winds have a fixed velocity of 500 km s$^{-1}$ with a mass upload rate equal to twice the local SFR, and carry away a fixed fraction (50 per cent) of the SN energy (for which the canonical value of $10^{51}$ erg is adopted). Finally, the run assumes a metallicity-dependent radiative cooling (Sutherland & Dopita 1993) and a uniform redshift-dependent UVB produced by quasars and galaxies as given by Haardt & Madau (1996).

Galaxies are recognized as gravitationally bound groups of at least 20 total (DM+gas+star) particles using the Amiga Halo Finder (AHF; Knollmann & Knebe 2009). When compared to the standard Sheth–Tormen mass function (Sheth & Tormen 1999), the simulated mass function is complete for halo masses $M_\bullet \geq 10^{10.5} M_\odot$ for $z \simeq 6$–8; galaxies above this mass cut-off are referred to as the ‘complete sample’. Of this complete sample, we identify all the ‘resolved’ galaxies that contain a minimum of 4N gas particles, where $N = 40$ is the number of nearest neighbours used in the SPH computations; this is twice the standard value of 2N gas particles needed to obtain reasonable and converging results (e.g. Bate & Burkert 1997). We impose an additional constraint and only use those resolved galaxies that contain at least 10 star particles so as to get a statistical estimate of the composite spectral energy distribution (SED). For each resolved galaxy used in our calculations (with $M_\bullet \geq 10^{9.5} M_\odot$, more than 4N gas particles and a minimum of 10 star particles), we obtain the properties of all its star particles, including the redshift and mass-metallicity at formation; we also compute global properties including the total stellar mass ($M_\star$), gas mass ($M_g$), DM mass ($M_D$), mass-weighted stellar metallicity ($Z_*$) and the mass weighted stellar age ($t_\star$).

2.2 Dust model

The evidence for dust at high redshifts comes from observations of damped Ly$\alpha$ systems (Pettini et al. 1994; Ledoux, Bergeron & Pettigrew 2002) and from the thermal dust emission from SDSS QSOs (Omont et al. 2001; Bertoldi & Cox 2002). Although dust is produced both by SN and evolved stars, several works (Todini & Ferrara 2001; Dwek, Galliano & Jones 2007) have shown that the contribution of asymptotic giant branch (AGB) stars to the total dust content is negligible at $z \gtrsim 6$, since the age of the Universe is shorter than the typical evolutionary time-scales of AGB stars above this redshift. We therefore make the hypothesis that Type II SN (SNI) are the primary dust factories and compute the total dust mass, $M_d$, in each of our simulated galaxies as described in Dayal, Ferrara & Saro (2010).

This dust mass can be used to obtain the total optical depth, $\tau_c$, to continuum photons as

$$\tau_c = \frac{3\Sigma_d}{4a_\star},$$

where $\Sigma_d = M_d/[\pi r_d^2]$ is the dust surface mass density, $r_d$ is the dust distribution radius, $a = 0.05$ $\mu$m and $s = 2.25$ g cm$^{-3}$ are the radius and material density of graphite/carbonaceous grains, respectively (Todini & Ferrara 2001). Since in our model dust and gas are assumed to be perfectly mixed, the dust distribution radius is taken to be equal to the gas distribution radius $r_g = 4.5\Delta r_{\text{vir}}$, where the spin parameter ($\lambda$) has a value of about 0.04 averaged across the galaxy population studied (Barnes & Efstathiou 1987; Steinmetz & Bartelmann 1995; Ferrara, Pettini & Shchekinov 2000) and $r_{\text{vir}}$ is the virial radius, calculated assuming that the collapsed region has an overdensity of 200 times the critical density. This dust optical depth can then be used to obtain the escape fraction of UV photons ($f_e$) assuming a screen-like dust distribution such that $f_e = e^{-\tau_c}$.

2.3 Identifying LBGs

To identify the simulated galaxies that could be observed as LBGs at $z \simeq 6$–8, we start by computing their UV luminosities. The total SED, including both the stellar and nebular continuum, is computed for each star particle via the population synthesis code STARburst99 (Leitherer et al. 1999), using its mass, stellar metallicity and age. The total intrinsic UV luminosity, $L_{\text{UV}}^\text{int}$ (at 1500 Å in the galaxy rest frame) is then calculated for each progenitor by summing the SEDs of all its star particles.

Continuum photons can be absorbed by dust within the ISM and only a fraction, $f_e$, escape out of any galaxy unattenuated by dust. However, these photons are unaffected by the ionization state of the IGM, and all the continuum photons that escape out of a galaxy can then reach the observer, so that the observed continuum luminosity can be expressed as $L_{\text{UV}}^{\text{obs}} = L_{\text{UV}}^\text{int} \times f_e$; this can be translated into an absolute magnitude, $M_{\text{UV}}$. In accordance with current observational criterion, at each redshift $z \simeq 6$–8, resolved simulated galaxies with $M_{\text{UV}} \leq -17$ are identified as LBGs.

3 COMPARING THE SIMULATIONS WITH LBG OBSERVATIONS

Once we have identified the simulated galaxies that would be detected as LBGs in the snapshots at $z \simeq 6$–8, we compare their UV LFs, stellar mass functions, SMDs and sSFRs to the observed values in order to validate the simulations used in this work. In this section, we show a comparison between the intrinsic and dust-attenuated (observed) theoretical UV LFs and the data. The theoretical stellar mass functions, SMD and sSFR, and their comparison with observed values are shown in Appendix A.

We calculate the intrinsic UV LFs by binning simulated LBGs on the basis of their intrinsic (i.e. dust-unattenuated) UV magnitudes.
and dividing this by the width of the UV bin (0.5 dex) and the volume of the box. We find that the intrinsic UV LF shifts towards brighter luminosities and higher number densities with decreasing redshift from $z \simeq 8$ to $6$, as expected from the hierarchical structure formation scenario where successively larger systems build up with time from the merger of smaller systems. As seen in Fig. 1, we find that the simulated intrinsic LBG UV LFs are overestimated with respect to the data, with the overestimation increasing with decreasing redshift, hinting at the increasing dust enrichment of these galaxies; we note that the intrinsic UV LF at $z \simeq 8$ is already in agreement with the observations, requiring no dust correction at this redshift.

We then use the observed (i.e. dust-attenuated) UV luminosity obtained for each galaxy at $z \simeq 6$–8 (see Sections 2.2 and 2.3) to build the observed UV LF. It is encouraging to note that both the slope and the amplitude of the dust-attenuated simulated LFs are in agreement with the observations for $z \simeq 6$ and 7 as seen from Fig. 1; as mentioned before, the simulated UV LF at $z \simeq 8$ requires no dust to match the observations. As can be seen from the same figure, the effects of dust on continuum photons at $z \simeq 6$, 7 are most severe for the most massive/luminous galaxies; indeed while $f_d \simeq 0.8$ for galaxies in halo masses of $M_h \lesssim 10^{10} M_\odot$, the value drops steadily thereafter such that $f_d \simeq 0.01$ for the largest galaxies at both $z \simeq 6$, 7. Further, as a result of galaxies typically being less massive, younger, and hence less dust enriched with increasing redshift, averaged over all LBGs $f_d$ drops from $\gtrsim 1$ at $z \simeq 8$ to 0.6 at $z \simeq 7$ and 0.5 at $z \simeq 6$. We briefly digress to note that these average $f_d$ values are about a factor of 2 higher than the values inferred in Dayal et al. (2010). This is due to the different feedback models implemented in these two simulations: while only 25 per cent of the SN energy was used to power outflows in the simulation used in Dayal et al. (2010), 50 per cent of the SN energy has been used to power outflows in the simulation used in this work. As a result of the much larger energy inputs that power SN winds in driving out gas from the galaxy, the typical stellar masses and SFRs obtained from the simulation used in this work are about a factor of 2 lower than those presented in Dayal et al. (2007, filled squares), McLure et al. (2009, filled circles); (b) $z \simeq 7$: Bouwens et al. (2011, filled squares), McLure et al. (2010, empty circles), McLure et al. (2013, filled circles), Oesch et al. (2010, filled triangles) and (c) $z \simeq 8$: Bradley et al. (2012, filled triangles), Bouwens et al. (2011, filled squares), McLure et al. (2010, empty circles) and McLure et al. (2013, filled circles).

Returning to our discussion regarding the observed LBG UV LFs, we notice that these also shift to progressively higher luminosities and/or higher number densities with decreasing redshift. Dayal et al. (2013) have shown that this evolution depends on the luminosity range probed: the steady brightening of the bright end of the LF is driven by genuine physical luminosity evolution due to a fairly steady increase in the UV luminosity (and hence SFRs) in the most massive LBGs; the evolution at the faint end arises due to a mixture of both positive and negative luminosity and density evolution as these putative systems brighten and fade, and continuously form and merge into larger systems.

Finally, we find that the best-fitting Schechter parameters to the dust-attenuated simulated UV LFs are faint-end slope $\alpha = (-1.9 \pm 0.2, -2.0 \pm 0.2, -1.8 \pm 0.2)$ and the knee of the LF $M_{\text{UV},*} = (-19.8 \pm 0.3, -19.7 \pm 0.2, -19.9 \pm 0.3)$ at $z = (6, 7, 8)$. These values are in agreement with the values $\alpha = (-1.71 \pm 0.11, -1.90 \pm 0.14, -2.02 \pm 0.22)$, $M_{\text{UV},*} = (-20.04 \pm 0.12, -19.9 \pm 0.2, -20.12 \pm 0.37)$ and $\alpha = (-1.74 \pm 0.16, -2.01 \pm 0.21, -1.91 \pm 0.32)$, $M_{\text{UV},*} = (-20.24 \pm 0.19, -20.14 \pm 0.26, -20.1 \pm 0.52)$ inferred observationally by McLure et al. (2009, 2013) and Bouwens et al. (2011) at $z \simeq (6, 7, 8)$, respectively.

### 4 SIMULATING LAES

In the previous section (and Appendix A), we have validated that the simulated galaxy population at $z \simeq 6$–8 is in agreement with a number of high-$z$ LBG observations. We now use these galaxy populations to identify the simulated galaxies that could be detected as LAEs. We start by describing the RT code (pcRASH) used to obtain reionization topologies for $f_{esc} = 0.05, 0.25, 0.5, 0.75, 0.95$, which are utilized to calculate the IGM Ly$\alpha$ transmission. We then describe how these transmission values, and the effects of dust on Ly$\alpha$ photons, are taken into account, so as to obtain the observed Ly$\alpha$ luminosity from the intrinsic value for each galaxy. We note that all the RT and Ly$\alpha$ calculations are carried out using a single snapshot of the hydrodynamical simulation at the edge of the reionization epoch, at $z \simeq 6.7$. 

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**Figure 1.** UV LFs at $z \simeq 6$, 7 and 8, from left to right, as marked in each panel. In all panels, the solid black (dashed red) histograms show the dust-corrected (intrinsic) simulated UV LFs with error bars showing the Poissonian error and symbols showing the observed data. The observed UV LFs have been taken from (a) $z \simeq 6$: Bouwens et al. (2007, empty squares), McLure et al. (2009, filled circles); (b) $z \simeq 7$: Bouwens et al. (2011, filled squares), McLure et al. (2010, empty circles), McLure et al. (2013, filled circles), Oesch et al. (2010, filled triangles) and (c) $z \simeq 8$: Bradley et al. (2012, filled triangles), Bouwens et al. (2011, filled squares), McLure et al. (2010, empty circles) and McLure et al. (2013, filled circles).
4.1 Reionizing the Universe with PCRASH

As mentioned in Section 1, the progress of reionization critically depends on the total number of H\textsc{i} ionizing photons that can escape a galaxy and ionize the IGM around it. As expected, this depends both on the total number of H\textsc{i} ionizing photons produced by a galaxy, as well as the fraction that can escape the galactic environment (f_{\text{esc}}). While the simulated SFRs are in reasonable agreement with observations (see Appendix A), giving us a handle on the H\textsc{i} ionizing photon production rate, the value of f_{\text{esc}} remains only poorly understood: using a variety of theoretical models, the value of f_{\text{esc}} has been found to range between 0.01 and 0.8 (see e.g. Ricotti & Shull 2000; Fujita et al. 2003; Razoumov & Sommer-Larsen 2006; Wise & Cen 2009).

Due to the poor theoretical constraints available on the value of f_{\text{esc}}, we do not make any prior assumptions on its value. We instead post-process the hydrodynamical simulation snapshot at $z \simeq 6.7$ with the RT code PCRASH using five different values of f_{\text{esc}} = 0.05, 0.25, 0.50, 0.75 and 0.95 to study how varying f_{\text{esc}} affects the progress of reionization.

We now briefly describe PCRASH, and interested readers are referred to Ciardi et al. (2001), Maselli, Ferrara & Ciardi (2003), Maselli, Ciardi & Kanekar (2009) and Partl et al. (2011) for more details. PCRASH is a 3D grid-based MPI-parallelized RT code that utilizes a combination of ray tracing and Monte Carlo schemes. It follows the time evolution of the IGM gas properties including ionization fractions (H\textsc{i} and He\textsc{i}, He\textsc{ii}) as well as the heating/cooling of the IGM (collisional ionization cooling, recombination cooling, collisional excitation cooling, bremsstrahlung, Compton cooling/heatng, adiabatic cooling, photoheating) are calculated. In addition, the code includes diffuse radiation following reionization fields obtained for different f_{\text{esc}} values. For each resolved source in the SPH simulation as the inputs for PCRASH. For each resolved source in the SPH simulation, the luminosity and spectrum were calculated by summing up the spectra of all their star particles, as described in Section 2.3; we processed 31,855 resolved sources from the snapshot at $z \simeq 6.7$. The spectrum of each source was binned into 125 frequency intervals ranging from 3.21 x 10^{15} to 3.30 x 10^{16} Hz. Each source emitted 10^{9} rays and we used 10^{6} timesteps per 500Myr on a 128^3 grid; we used the mean local clumping factor of each cell obtained from the underlying density distribution from the SPH simulation to account for the clumpiness of the IGM (Raičević & Theuns 2011). Depending on the escape fraction, the runs were carried out on 64 or 128 processors on AIP clusters. Each simulation was run until the IGM global hydrogen fraction dropped to $\langle x_{\text{H}\text{i}} \rangle \lesssim 10^{-4}$, so that the entire progress of reionization could be mapped.

We now discuss the ionization fields obtained by running PCRASH on the SPH simulation snapshot at $z \simeq 6.7$ for the five different f_{\text{esc}} values mentioned above. First, the volume of the ionized region ($V_{i}$) carved out by any source depends on its total ionizing photon output such that

$$V_{i} \propto \frac{Q f_{\text{esc}}}{x_{\text{H}\text{i}} n_{\text{H}}},$$

where $Q$ is the total number of H\textsc{i} ionizing photons produced by the source, $x_{\text{H}\text{i}}$ is the H\textsc{i} fraction and $n_{\text{H}}$ represents the number density of hydrogen atoms. From this expression, it is clear that for a given source surrounded by an IGM of a given H\textsc{i} density, $V_{i}$ increases with $f_{\text{esc}}$. In other words, given a galaxy population, at any given time, the IGM is more ionized (i.e. reionization proceeds faster) for larger $f_{\text{esc}}$ values.

Secondly, the photoionization rate ($\Gamma(r)$) at a distance $r$ from a source depends on the source H\textsc{i} photon emissivity ($L_{\text{f_{\text{esc}}}}$) such that

$$\Gamma(r) = \int_{0}^{\lambda_{\lambda}} \frac{L_{\text{f_{\text{esc}}}} f_{\text{esc}}}{4 \pi r^{2}} \sigma_{1} \left( \frac{\lambda}{\lambda_{\text{L}}} \right)^{3} \frac{\lambda}{hc} d\lambda,$$

where $L_{i}$ is the total specific ionizing luminosity of the emitter, $\lambda_{\lambda}$ is the Lyman limit wavelength (912 Å), $\sigma_{1}$ is the hydrogen photoionization cross-section at $\lambda = \lambda_{\lambda}$, $h$ is the Planck constant and $c$ represents the speed of light. Assuming ionization–recombination balance, it is this photoionization rate that determines the level of ionization, $x_{\text{H}\text{i}}$, around an emitter. Hence, for a given emitter, $x_{\text{H}\text{i}}$ is expected to decrease for increasing values of $f_{\text{esc}}$ (see also section 2.4 in Dayal et al. 2008).

These two effects can be clearly seen in Figs 2 and 3: the former and latter show the ionization fields obtained for different $f_{\text{esc}}$ by running PCRASH for a given time (50 Myr) and until the IGM is ionized to a level of $\langle x_{\text{H}\text{i}} \rangle \simeq 0.1$, respectively. From Fig. 2, it can be clearly seen that reionization proceeds faster for increasing $f_{\text{esc}}$ values: after 50 Myr of running PCRASH, while the largest ionized region built has a size of about 15 cMpc for $f_{\text{esc}} = 0.05$, the entire box is almost reionized for $f_{\text{esc}} = 0.95$. Indeed, the average value of $x_{\text{H}\text{i}}$ drops steadily with increasing $f_{\text{esc}}$ such that $\langle x_{\text{H}\text{i}} \rangle = (0.97, 0.82, 0.62, 0.37, 0.20)$ for $f_{\text{esc}} = (0.05, 0.25, 0.5, 0.75, 0.95)$, respectively. Increasing $f_{\text{esc}}$ by a factor of 19, from 0.05 to 0.95, has the effect of decreasing the neutral hydrogen fraction; while the IGM is essentially neutral for $f_{\text{esc}} = 0.05$, it is almost ionized for $f_{\text{esc}} = 0.95$.

From Fig. 3, we find that the topology of reionization looks similar for all the five $f_{\text{esc}}$ values by the time the average H\textsc{i} fraction has dropped to $\langle x_{\text{H}\text{i}} \rangle = 0.1$. However, the time taken to reach this average ionization state is very different for the five runs; while the run with $f_{\text{esc}} = 0.95$ took 80 Myr to reach this ionization level, the runs with $f_{\text{esc}} = 0.05$ took about 10 times longer ($\approx 800$ Myr) to build up these ionized regions. We also note that although the spatial distribution of the ionization fields looks very similar for the varying $f_{\text{esc}}$ values, the level of ionization in any given cell increases with increasing $f_{\text{esc}}$ as seen from the same figure (see also equation 3).

To summarize, we find that increasing $f_{\text{esc}}$ both accelerates the progress of reionization and leads to higher ionization fractions in the ionized regions. A combination of both these factors leads to a larger IGM Ly\text{a} transmission $T_{\alpha}$ with increasing $f_{\text{esc}}$, as explained in the following.

4.2 Identifying LAEs

In this section, we start by explaining how we calculate the intrinsic Ly\text{a} luminosity produced by each simulated galaxy at $z \simeq 6.7$. We then show how we calculate the Ly\text{a} attenuation by ISM dust and IGM H\textsc{i} to determine the fraction of this intrinsic luminosity that is finally observed.

4.2.1 Intrinsic Ly\text{a} luminosity

As mentioned above, SF in galaxies produces photons more energetic than 1 Ryd, with a certain fraction ($f_{\text{esc}}$) escaping into and ionizing the IGM. The rest of these photons ($1 - f_{\text{esc}}$) ionize the H\textsc{i}
Figure 2. Maps (80 $h^{-1}$ Mpc on a side) of the spatial distribution of H I in a 2D cut through the centre of the simulated box at $z \simeq 6.7$ obtained by running PCRASH for 50 Myr using the $f_{\text{esc}}$ value marked above the panel. The colour bar shows the values (in log scale) of the H I fraction. As can be seen, reionization proceeds faster with increasing $f_{\text{esc}}$ values.

Figure 3. Maps (80 $h^{-1}$ Mpc on a side) of the spatial distribution of H I in a 2D cut through the simulated box at $z \simeq 6.7$ obtained by running PCRASH using the $f_{\text{esc}}$ value marked above the panel, until the average neutral hydrogen fraction drops to $\langle \chi_{\text{HI}} \rangle \simeq 0.1$. The colour bar shows the values (in log scale) of the H I fraction. As seen, while the topology of reionization looks very similar for the same average H I values, the degree of ionization close to any source increases with increasing $f_{\text{esc}}$. 
in the ISM. Due to the high density of the ISM, these electrons and protons recombine on very short time-scales giving rise to a Lyα emission line of luminosity

\[ L^\text{int}_\alpha = \frac{2}{3} Q(1 - f_\text{esc}) h v_e, \]  

(4)

where the factor 2/3 arises due to our assumption of case-B recombinations for optically thick H_\text{I} in the ISM (Osterbrock 1989) and \( v_e \) represents the Lyα frequency in the galaxy rest frame.

However, this line is Doppler broadened by the rotation of the galaxy so that the complete line profile can be expressed as

\[ L^\text{int}_\alpha(v) = \frac{2}{3} Q(1 - f_\text{esc}) h v_e \frac{1}{\sqrt{\pi} \Delta v_d} \exp \left[ \frac{-(v - v_e)^2}{\Delta v_d^2} \right], \]  

where \( \Delta v_d = (v_c/c) v_e \). For realistic halo and disc properties, the rotation velocity of the galaxy \( v_c \) can range between \( v_b \) and \( 2v_b \), where \( v_b \) is the halo rotation velocity (Mo, Mao & White 1998; Cole et al. 2000). We use the central value of \( v_c = 1.5 v_b \) in all the calculations presented in this paper.

### 4.2.2 Effects of dust

The intrinsic Lyα luminosity produced by a galaxy has to penetrate through dust in the ISM, with only a fraction \( f_d \) escaping out of the galactic environment. In Section 2.2, we have shown calculations for the total dust enrichment of each simulated galaxy and the resulting value of \( f_d \). The relation between \( f_d \) and \( f_r \) depends on the adopted extinction curve if dust is homogeneously distributed; it also depends on the differential effects of RT on Lyα and UV photons if dust is inhomogeneously distributed (clumped (Neufeld 1991; Hansen & Oh 2006). While some pieces of evidence exist that show the extinction curve (Bianchi & Schneider 2007) can successfully be used to interpret the observed properties of the most distant quasars (Maiolino et al. 2006) and gamma-ray bursts (Stratta et al. 2007), the effect of dust inhomogeneities in enhancing the escape fraction of Lyα photons with respect to continuum photons through the Neufeld effect (Neufeld 1991) remains controversial.

On the one hand, Finkelstein et al. (2009) have found tentative observational evidence of \( f_d/f_r > 1 \) for \( z \approx 4.5 \) LAEs, and Dayal et al. (2009, 2011) have shown that models require \( f_d/f_r > 1 \) to reproduce LAE data at \( z \lesssim 6 \). On the other hand, Laursen, Duval & Östlin (2013) have shown that a value of \( f_d/f_r \) requires very special circumstances (no bulk outflows, very high metallicity, very high density of the warm neutral medium and a low-density and highly ionized medium) that are unlikely to exist in any realistic ISM; moreover, they show that a value of \( f_d/f_r > 1 \) results in very narrow Lyα lines that are sensitive to infalling gas, resulting in low \( T_\alpha \) values. Due to its poor understanding, the relative escape fraction \( f_d/f_r \) is left as a free parameter in our model and its value is fixed by matching the theoretical LAE Lyα and UV LFs to the observations, as shown in Section 5 that follows.

### 4.2.3 Effects of the IGM

The Lyα photons that escape out of a galaxy unabsorbed by dust are attenuated by the H_\text{I}; they encounter along the LOS between the emitter and the observer, with a fraction \( T_\alpha = e^{-\tau_\alpha} \) being transmitted through the IGM. This optical depth to H_\text{I} \( (\tau_\alpha) \) can be calculated as

\[ \tau_\alpha = \int_{r_{\text{em}}}^{r_{\text{obs}}} \sigma_0 \Phi(v + v_\text{p}(r)) n_{\text{HI}}(r) \, dr, \]  

where \( v = (\lambda - \lambda_0)\lambda_0^{-1}c \) is the rest-frame velocity of a photon with frequency \( \lambda \) relative to the Lyα line centre at \( \lambda_0 = 1216 \) Å. Further, \( v_\text{p} \) accounts for the IGM peculiar velocity, \( n_{\text{HI}}(r) \) is the H_\text{I} density at a physical distance \( r \) from the emitter, \( \sigma_0 = \pi e^2 f/m_e c \) is the absorption cross-section, \( f \) is the oscillator strength, \( e \) is the electron charge, \( m_e \) is the electron mass and \( \Phi(v) \) is the Voigt profile; this profile consists of a Gaussian core and Lorentzian damping wings. For regions of low H_\text{I} density, pressure line broadening becomes unimportant and the line profile can be approximated by the Gaussian core. However, the Lorentzian damping wings become important in regions of high H_\text{I} density and the complete profile must then be used. Although it is computationally quite expensive, we use the complete Voigt profile for all our calculations. We note that we include the effects of peculiar velocities \( (v_\text{p}) \) in determining \( \tau_\alpha \): inflows (outflows) of gas towards (from) a galaxy will blueshift (redshift) the Lyα photons, increasing (decreasing) \( \tau_\alpha \), which leads to a corresponding decrease (increase) in \( T_\alpha \). We compute \( \tau_\alpha \) by stepping through our simulation box which is divided into a grid of 128^3 cells, with each cell having a size of 117 physical kpc; this is the same grid that is used in the PCRASH, as described in Section 4.1. For any galaxy, we start calculating \( \tau_\alpha \) at the galaxy position \( r_{\text{em}} = 0 \), until the edge of the box is reached \( r_{\text{obs}} \). The values of \( v_\text{p}(r) \) and \( n_{\text{HI}}(r) \) in each cell are then obtained from \textsc{gadget-2} and \textsc{pcrash} runs, respectively. A single \textsc{gadget-2} snapshot at \( z \approx 6.7 \) suffices for our work because the Lyα line redshifts out of resonance with H_\text{I} extremely quickly; to a first approximation, the spatial scale imposed by the Gunn–Peterson damping wing on the size of the H_\text{I} region corresponds to a separation of about 280 kpc (physical) at \( z = 6 \) (Miralda-Escude 1998). Interested readers are referred to Dayal et al. (2011) for complete details of this calculation.

We use the ionization fields obtained by running \textsc{pcrash} (see Section 4.1) with the five different \( f_{\text{esc}} \) values to calculate the average \( T_\alpha \) for each galaxy along 48 LOS. For a given ionization state, the final \( T_\alpha \) value of each galaxy is taken to be the average along all 48 LOS. For each galaxy, we compute the observed Lyα luminosity \( L^{\text{obs}}_\alpha \) by using the individual values for \( f_d \) and \( T_\alpha \) of the respective galaxy,

\[ L^{\text{obs}}_\alpha = f_d T_\alpha L^{\text{int}}_\alpha. \]  

(7)

In consistency with current observational criteria, galaxies with \( L^{\text{obs}}_\alpha \geq 10^{42} \) erg s^{-1} and an equivalent width \( (EW = L^{\text{obs}}_\alpha / L^{\text{obs}}_{\text{Ly}\alpha} \geq 20 \) Å) are then identified as LAEs and used to build the LAE UV and Lyα LFs. We note that the Lyα LFs along different LOS are subject to cosmic variance as shown in Appendix B.

We also remind the reader that \( T_\alpha \) is fixed from the ionization state of the IGM as explained above. Then, the only free parameter that we are left with to identify LAEs is the relative escape fraction of Lyα and continuum photons, i.e. \( f_d/f_r \). This final free parameter is fixed by matching the simulated LFs to the observed ones, as explained in Section 5.

Before proceeding to a comparison between the theoretical results and observational data, we briefly digress to show the relation between \( T_\alpha \) and \( \langle \chi_{\text{HI}} \rangle \) for our five \( f_{\text{esc}} \) values. As can be seen from Fig. 4 (see also Section 4.1), the mean IGM transmission \( \langle T_\alpha \rangle \) averaged over all galaxies increases with decreasing \( \langle \chi_{\text{HI}} \rangle \) values: as ionized regions grow larger, they allow all galaxies to transmit more of their Lyα flux through the IGM. The inhomogeneity of the ionized regions also leads to a huge variation in \( T_\alpha \) as seen from the 1σ dispersions in the same figure. Finally, our mean IGM transmission values are consistent with the results obtained by Jensen et al. (2013), Iliev et al. (2008) and Dijkstra et al. (2007) for \( f_{\text{esc}} = 0.05; \)
we note that Ly$\alpha$ transmission calculations have not been performed for escape fractions higher than this value.

5 Joint Constraints on Reionization Topology and Dust

From Sections 4.1 and 4.2, it is clear that $f_{\text{esc}}$ affects the observed Ly$\alpha$ luminosity both through its effect on the intrinsic Ly$\alpha$ luminosity and through its effect on the ionization state of the IGM. Further, for a given $f_{\text{esc}}$ and ionization state, the only free parameter left in our model is the escape fraction of Ly$\alpha$ photons compared to UV-continuum photons, $f_{\alpha}/f_{\text{c}}$. In this section, we use the LAE data accumulated by Kashikawa et al. (2011) to simultaneously constrain and find best fits to our three parameters, $f_{\text{esc}}$, $\langle \chi_{\text{H}} \rangle$, and $f_{\alpha}/f_{\text{c}}$. We use $\text{PCrash}$ outputs for $\langle \chi_{\text{H}} \rangle \simeq 0.9$, $0.75$, $0.5$, $0.25$, $0.1$, $0.01$ and $10^{-4}$ for each of the five $f_{\text{esc}} = 0.05$, $0.25$, $0.5$, $0.75$, $0.95$ at $z \simeq 6.7$. For each such combination, we start from the special case of assuming $f_{\alpha}/f_{\text{c}} = 0.68$ which corresponds to dust being homogeneously distributed in the ISM in Section 5.1, and progress to the more general scenario of varying $f_{\alpha}/f_{\text{c}}$ to best fit the observations, in Section 5.2.

5.1 A special case: homogeneous dust

As shown in equation (4), the intrinsic Ly$\alpha$ luminosity produced by a galaxy depends on the fraction of H$\text{I}$ ionizing photons that ionize the H$\text{I}$ in the ISM. It is thus naturally expected that $L_{\text{int}}$ decreases with increasing $f_{\text{esc}}$ since this leads to fewer photons being available for ionization in the ISM. This behaviour can be seen from panel (a) of Fig. 5, where we find that the amplitude of the Ly$\alpha$ LF drops by a factor of about 40 as $f_{\text{esc}}$ increases from 0.05 to 0.95. This drop seems surprising at the first glance: as $f_{\text{esc}}$ increases by a factor of about 19, the intrinsic Ly$\alpha$ LF would be expected to drop by the same amount. However, this result can be easily explained by the fact that we identify galaxies as LAEs based on the Ly$\alpha$ luminosity being larger than $10^{42}$ erg s$^{-1}$ and an EW $\geq 20$ Å. As $f_{\text{esc}}$ increases, fewer and fewer galaxies are able to fulfil these selection criteria, leading to an enhanced drop in the amplitude of the Ly$\alpha$ LF.

The ratio $f_{\alpha}/f_{\text{c}}$ depends on many physical effects (see e.g. Laursen et al. 2013), including the distribution of the Ly$\alpha$ sources in the dusty ISM (Scarlata et al. 2009), the ISM H$\text{I}$ column densities and velocities. However, a natural consequence of simulating cosmological volumes is that we are unable to resolve the ISM of individual galaxies. We therefore start with the special scenario wherein dust is homogeneously distributed in the ISM and Ly$\alpha$ photons are not scattered by dust and H$\text{I}$ within the ISM. Since SNII are assumed to be the main sources of dust in our model, we deduce the ratio $f_{\alpha}/f_{\text{c}} = 0.68$ purely from the corresponding SN extinction curve (Bianchi & Schneider 2007). This fixed ratio is then applied uniformly to all galaxies in the simulation snapshot at $z \simeq 6.7$. Once $f_{\alpha}$ has been fixed using this ratio, the only two parameters that can affect the slope and amplitude of the Ly$\alpha$ LFs are $f_{\text{esc}}$ and $\chi_{\text{H}}$.

We start by discussing the Ly$\alpha$ LF evolution as a function of $\langle \chi_{\text{H}} \rangle$. As expected from equation (6), for a given $f_{\text{esc}}$, $\tau_{\alpha}$ decreases with decreasing $\langle \chi_{\text{H}} \rangle$, leading to an increase in the ISM Ly$\alpha$ transmission. This naturally results in an increase in the amplitude of the Ly$\alpha$ LF by making galaxies more luminous in the observed Ly$\alpha$ luminosity, $L_{\alpha}^{\text{obs}}$, as can be seen from panels (b)–(e) of Fig. 5. However, the effect of decreasing $\chi_{\text{H}}$ is the strongest on the visibility of the faintest galaxies and decreases with increasing luminosity. This is because the spatial scale imposed by the Gunn–Peterson damping wing on the size of the H$\text{II}$ region corresponds to a separation of about 280 kpc (physical) at $z \simeq 7$ (Miralda-Escude 1998). The most massive galaxies are easily able to carve out H$\text{II}$ regions of this size as a result of their relatively large H$\text{I}$ ionizing photon output. However, in the initial stages of reionization, only those faint galaxies that are clustered are able to build H$\text{II}$ regions of this size and become visible as LAEs (McQuinn et al. 2007b; Dayal et al. 2009). Hence, for a given $f_{\text{esc}}$, the faint-end slope of the Ly$\alpha$ LF becomes steeper with decreasing $\langle \chi_{\text{H}} \rangle$ values as seen from panels (b)–(e) of Fig. 5. We also see that the slope and amplitude of the Ly$\alpha$ LFs start converging for $\langle \chi_{\text{H}} \rangle \simeq 10^{-2}$; this corresponds to the average H$\text{I}$ fraction at which galaxies typically inhabit H$\text{II}$ regions such that the red part of the Ly$\alpha$ line escapes unattenuated by H$\text{I}$.

We now discuss the evolution of the Ly$\alpha$ LFs with $f_{\text{esc}}$. As we have already noted in Fig. 3, although the spatial distribution of the ionization fields looks very similar for the varying $f_{\text{esc}}$ values for a given $\langle \chi_{\text{H}} \rangle$, the $\chi_{\text{H}}$ value in any given cell decreases with increasing $f_{\text{esc}}$. This leads to an increase in $T_{\alpha}$ with $f_{\text{esc}}$ such that for $\langle \chi_{\text{H}} \rangle \simeq 0.1$, averaged over all LAEs, $\langle T_{\alpha} \rangle = (0.43, 0.45, 0.48, 0.59)$ for $f_{\text{esc}} = (0.05, 0.25, 0.50, 0.75)$. However, this slight increase in $T_{\alpha}$ is compensated by the decrease in the intrinsic Ly$\alpha$ luminosity with increasing $f_{\text{esc}}$ as shown in panel (a) of Fig. 5. As a result, the amplitude of the resulting Ly$\alpha$ LFs decreases slightly as $f_{\text{esc}}$ increases from 0.05 to 0.5 for a given $\langle \chi_{\text{H}} \rangle$; however, the slopes are very similar since $f_{\text{esc}}$ affects the intrinsic luminosity of all simulated galaxies by the same factor. The Ly$\alpha$ LF drops steeply between $f_{\text{esc}} = 0.5$ and 0.75, and there are no simulated galaxies that would be identified as LAEs for $f_{\text{esc}} = 0.95$. This steep drop for $f_{\text{esc}} > 0.5$ arises due to our imposed criterion of the observed Ly$\alpha$ EW being larger than 20 Å. For a continually star-forming galaxy with an age of about 200 Myr, a stellar metallicity of $Z_{\odot} = 0.02 Z_{\odot}$ and $f_{\alpha} = 0$, the intrinsic Ly$\alpha$ EW has a value of about 114 Å; we note that this intrinsic EW would decrease for increasing values of $Z_{\odot}$ and $f_{\text{esc}}$. For a value of $f_{\text{esc}} = (0.75, 0.95)$, this intrinsic EW then reduces to about (28.5, 5.7) Å. Then, taking into account the effect of the IGM transmission, very few (none) of our simulated galaxies fulfil the EW selection criterion for $f_{\text{esc}} = 0.75 (0.95)$ leading to a
Figure 5. The cumulative Lyα LFs. Panel (a) shows the intrinsic Lyα LFs for escape fractions $f_{\text{esc}} = 0.05, 0.25, 0.50, 0.75$, as marked. The lines in the other panels show the results for homogeneously distributed SNII dust ($f_\alpha / f_c = 0.68$) for different $\langle \chi_{HI} \rangle$ states ($\langle \chi_{HI} \rangle \approx 0.90, 0.75, 0.50, 0.25, 0.10, 0.01, 10^{-4}$) obtained using the fixed $f_{\text{esc}}$ value marked above the panel. In each panel, black open circles show the Lyα LFs at $z \approx 6.5$ inferred observationally by Kashikawa et al. (2011). Due to the EW selection criterion, no LAEs are identified for $f_{\text{esc}} = 0.95$. Finally, we note that both the slope and amplitude of the simulated Lyα LFs are in agreement with observations for $f_{\text{esc}} = 0.05$ and $\langle \chi_{HI} \rangle \leq 0.1$; for $f_{\text{esc}} \geq 0.25$, the simulated Lyα LFs are underestimated with respect to the data, even for a fully ionized IGM.

The UV LFs are not directly dependent on the IGM ionization state. However, both their slope and amplitude are affected by $\langle \chi_{HI} \rangle$ since these are the UV LFs for the simulated galaxies that would be identified as LAEs on the basis of $L_{\alpha}^{\text{obs}}$ and the EW. It is interesting to note that with our deeper Lyα luminosity limit of $L_{\alpha}^{\text{obs}} \geq 10^{42}$ erg s$^{-1}$ compared to the observational limit of $10^{42.4}$ erg s$^{-1}$, we find that the cumulative UV LFs keep rising until $M_{UV} \leq -19$ for $f_{\text{esc}} \leq 0.5$ as seen from panels (a)–(c) of Fig. 6. From the same panels, we find that the bright-end slope of the UV LF ($M_{UV} \leq -21.5$) matches the observed UV LFs for all values of $\langle \chi_{HI} \rangle$ and $f_{\text{esc}} \leq 0.5$. Further, the UV LFs start converging at much higher values of $\langle \chi_{HI} \rangle \approx 0.25$, compared to the value of 0.1 required for the Lyα LFs to settle. Similar to the behaviour seen for the Lyα LF, for a given $f_{\text{esc}} \leq 0.5$, the faint end of the UV LF steepens with decreasing $\langle \chi_{HI} \rangle \simeq 0.25$, compared to the value of 0.1 required for the Lyα LFs to settle. Again, for a given $\langle \chi_{HI} \rangle$, while the amplitude of the UV LFs decreases slightly between $f_{\text{esc}} = 0.05$ and 0.5, the slope remains the same. The steep drop in the number of LAEs for $f_{\text{esc}} \approx 0.75$ naturally leads to a drop in the UV LF shown in panel (d) of the same figure; as for the Lyα LF, the UV LF amplitude is zero for $f_{\text{esc}} = 0.95$ due to no simulated galaxies being classified as LAEs.

Finally, we note that by jointly reproducing the observed Lyα and UV LFs, we can constrain for $f_{\text{esc}} = 0.05$ one of the most important parameters for reionization: $\langle \chi_{HI} \rangle \leq 0.1$ or $\langle T_\alpha \rangle_{\text{LAE}} \geq 0.43$. However, we caution the reader that this result is only valid in the case where the ISM dust is homogeneously distributed. Since using only the UV LFs allows a much larger parameter range of $\langle \chi_{HI} \rangle \leq 0.25$, a question that arises is whether this larger parameter space could also be reconciled with the Lyα LFs given clumped dust that could increase $L_{\alpha}^{\text{obs}}$ by increasing $f_\alpha$. We carry out these calculations in Section 5.2 that follows.

5.2 Clumped dust

A number of works have shown that inhomogeneously distributed (clumped) dust in the ISM can enhance the escape fraction of Lyα photons compared to UV photons which are not resonantly scattered by H I (Neufeld 1991; Hansen & Oh 2006). However, the amount by which the ratio $f_\alpha / f_c$ can be enhanced by clumped dust sensitively depends on the amount of dust that is bound in cold neutral gas clouds and the number of these encountered by Lyα photons within...
The cumulative UV LFs for simulated LAEs using a homogeneous dust case \((f_α/f_c = 0.68)\). The lines in the panels show the UV LFs for different \(\langle\chi_H\rangle\) states \((\langle\chi_H\rangle \approx 0.90, 0.75, 0.50, 0.25, 0.10, 0.01, 10^{-4}\)) obtained using the fixed \(f_{\text{esc}}\) value marked above the panel. In each panel, black open circles show the LAE UV LFs at \(z = 6.5\) inferred observationally by Kashikawa et al. (2011). The vertical grey dotted lines indicate the limiting 2\(\sigma\) magnitude in the \(\gamma\) band (see Kashikawa et al. 2011); measurements for fainter magnitudes may be uncertain because the corresponding \(\gamma\)-band magnitudes are no longer reliable. Due to the EW selection criterion, no LAEs are identified for \(f_{\text{esc}} = 0.95\).

Figure 6. The cumulative UV LFs for simulated LAEs using a homogeneous dust case \((f_α/f_c = 0.68)\). The lines in the panels show the UV LFs for different \(\langle\chi_H\rangle\) states \((\langle\chi_H\rangle \approx 0.90, 0.75, 0.50, 0.25, 0.10, 0.01, 10^{-4}\)) obtained using the fixed \(f_{\text{esc}}\) value marked above the panel. In each panel, black open circles show the LAE UV LFs at \(z = 6.5\) inferred observationally by Kashikawa et al. (2011). The vertical grey dotted lines indicate the limiting 2\(\sigma\) magnitude in the \(\gamma\) band (see Kashikawa et al. 2011); measurements for fainter magnitudes may be uncertain because the corresponding \(\gamma\)-band magnitudes are no longer reliable. Due to the EW selection criterion, no LAEs are identified for \(f_{\text{esc}} = 0.95\).

the galaxy. Since such sub-grid parameters cannot be resolved by our cosmological simulation, we use \(f_α/f_c\) as a free parameter and explore the range required to reproduce the data for the different \(f_{\text{esc}}\) and \(\langle\chi_H\rangle\) combinations discussed in Section 5.1.

As shown in Section 5.1, an increasing \(f_{\text{esc}}\) reduces the intrinsic Ly\(\alpha\) luminosity for all galaxies, leading to a drop in the amplitude of the Ly\(\alpha\) LF. However, since \(L_{\text{int}}^{\gamma} \propto (1 - f_{\text{esc}}) f_α T_α\), a decrease in the intrinsic Ly\(\alpha\) luminosity (due to an increasing \(f_{\text{esc}}\)) can be compensated by a larger fraction of Ly\(\alpha\) photons escaping out of the galaxy (i.e. a higher \(f_α\)) and/or a larger amount being transmitted through the IGM (i.e. a larger \(T_α\)). Hence, for a given \(\langle\chi_H\rangle\) (i.e. \(T_α\)) by allowing values of \(f_α/f_c > 0.68\), the amplitude of the Ly\(\alpha\) LF can be boosted. However, it is important to note that since we use a constant value of \(f_α/f_c \) for all galaxies, it only changes the amplitude of the Ly\(\alpha\) LF at the bright end; raising this ratio makes the faint-end slope slightly steeper since a number of galaxies which are at our detection limit (\(L_\alpha \geq 10^{42}\) erg s\(^{-1}\) and EW \(\geq 20\) \(\text{Å}\)) become visible as LAEs with increasing \(f_α/f_c\).

It is interesting to note that even using \(f_α/f_c\) ratios such that \(f_α\) saturates to 1, the simulated Ly\(\alpha\) LFs are well below the observations for \(\langle\chi_H\rangle \approx 0.75\), for all \(f_{\text{esc}} = 0.05\) to 0.95, as seen from panels (a)–(e) of Fig. 7. This is because the H\(\text{II}\) regions built by faint galaxies are too small to allow a large IGM Ly\(\alpha\) transmission, even for \(f_{\text{esc}} = 0.95\). We now discuss the results for varying \(f_{\text{esc}}\): as mentioned in Section 5.1, the Ly\(\alpha\) and UV LFs can be well reproduced using the homogeneous dust case \((f_α/f_c = 0.05)\) for \(\langle\chi_H\rangle \leq 0.1\). In the case of clumped dust, the simulated LFs match the observations for \(f_{\text{esc}} = 0.05\) for \(\langle\chi_H\rangle\) as high as 0.5, provided that the decrease in \(T_α\) is compensated by \(f_α/f_c\) increasing to 1.2 (see Table 1). For \(f_{\text{esc}} = 0.25, 0.5\), within a \(\sigma\) error the simulated LFs can be reconciled with the observations for \(\langle\chi_H\rangle \leq 0.5\), given that \(f_α/f_c\) increases to 1.6, 1.8, respectively, as shown in Table 1; however, due to a decrease in the intrinsic Ly\(\alpha\) luminosity and EW, the faint-end slope of the simulated LFs is always underestimated with respect to the data for \(\langle\chi_H\rangle \geq 0.5\). As \(f_{\text{esc}}\) increases to 0.75 and above, the amplitude of the Ly\(\alpha\) LFs cannot be boosted up to the observed value, even for \(f_α = 1\); although the H\(\text{II}\) regions built by these galaxies are very large as a result of the large H\(\text{i}\) ionizing photon escape fraction leading to large \(T_α\) values, the EW of the Ly\(\alpha\) line prevents most of these galaxies from being classified as LAEs (see also Section 5.1 above).

We therefore find a three-dimensional degeneracy between the IGM ionization state \(\langle\chi_H\rangle\), the escape fraction of H\(\text{i}\) ionizing photons \((f_{\text{esc}})\) and the clumped/inhomogeneous distribution of dust in the ISM of galaxies (governing \(f_α/f_c\)) such that a decrease in \(L_{\text{int}}^{\gamma}\) with increasing \(f_{\text{esc}}\) can be compensated by a larger \(T_α\) and \(f_α/f_c\). However, we find that the \(\langle\chi_H\rangle\) values which reproduce the observations decrease with increasing \(f_{\text{esc}}\) because an increasing \(f_α\) cannot compensate for the decrease in the intrinsic Ly\(\alpha\) luminosity. This degeneracy can be seen from Fig. 8, where we show...
Figure 7. The cumulative Ly$\alpha$ LFs. The panels show the best-fitting simulated results for the $f_{\text{esc}}/f_c$ values shown in Table 1. The panels show the results for different $\langle X_{HI} \rangle$ states ($\langle X_{HI} \rangle \simeq 0.90, 0.75, 0.50, 0.25, 0.10, 0.01, 10^{-4}$) obtained using the fixed $f_{\text{esc}}$ value marked above the panel. In each panel, black open circles show the Ly$\alpha$ LFs at $z \simeq 6.5$ inferred observationally by Kashikawa et al. (2011).

Table 1. For the $\langle X_{HI} \rangle$ value shown in column 1, for the $f_{\text{esc}}$ value shown as a subscript in each of the columns 2–4, we show the $f_{\alpha}/f_c$ ratio required to fit the simulated LAE Ly$\alpha$ and UV LFs to those observed by Kashikawa et al. (2011) within a 1$\sigma$ error.

<table>
<thead>
<tr>
<th>$\langle X_{HI} \rangle$</th>
<th>$f_{\alpha}/f_c$ (0.05)</th>
<th>$f_{\alpha}/f_c$ (0.25)</th>
<th>$f_{\alpha}/f_c$ (0.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>1.2</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>0.25</td>
<td>0.8</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>0.10</td>
<td>0.68</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>0.01</td>
<td>0.68</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>0.60</td>
<td>0.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>

contours of 1$\sigma$–5$\sigma$ deviations from the observations (Kashikawa et al. 2011), obtained by computing the $\chi^2$ values for all the combinations of $f_{\text{esc}} = (0.05, \ldots, 0.95)$, $\langle X_{HI} \rangle = (10^{-4}, \ldots, 0.90)$ and $f_{\alpha}/f_c = (0.60, \ldots, 1.8)$, as shown in Table 1.

The relation between $\langle X_{HI} \rangle$ and $\langle T_{\alpha}\rangle_{\text{LAE}}$ is complex due to the dependency upon the reionization topology as shown in Dijkstra et al. (2011; see also Fig. 4 and Jensen et al. 2013) and the assumed line shape (e.g. Gaussian, double-peaked; Laursen, Sommer-Larsen & Razoumov 2011; Jensen et al. 2013; Duval et al. 2014). For this reason, we also show the three-dimensional degeneracy in terms of the mean transmission across all LAEs $\langle T_{\alpha}\rangle_{\text{LAE}}$ for a given combination of $f_{\text{esc}}$ and $f_{\alpha}/f_c$ in Fig. 9.

We note that for a given $\langle X_{HI} \rangle$, the mean transmission of all LAEs $\langle T_{\alpha}\rangle_{\text{LAE}}$ decreases for increasing $f_{\alpha}/f_c$: with rising $f_{\alpha}/f_c$ more galaxies, with lower values of $T_{\alpha}$, are identified as LAEs, leading to a decline in $\langle T_{\alpha}\rangle_{\text{LAE}}$. This effect can be seen for the maximum $\langle T_{\alpha}\rangle_{\text{LAE}}$ values, within a 4$\sigma$ error, in each panel of Fig. 9, and it demonstrates the dependency of $\langle T_{\alpha}\rangle_{\text{LAE}}$ on $f_{\alpha}/f_c$.

From Figs 8 and 9, we see that within a 1$\sigma$ error, the observed Ly$\alpha$ and UV LFs can be reproduced for $f_{\text{esc}}$ values ranging between 0.05 and 0.5 and $\langle X_{HI} \rangle \simeq 10^{-4}$–0.5 or $\langle T_{\alpha}\rangle \simeq 0.38$–0.5, provided that the decreasing intrinsic Ly$\alpha$ luminosity (with increasing $f_{\text{esc}}$) and decreasing IGM transmission (with increasing $\langle X_{HI} \rangle$) are compensated by an increasing $f_{\alpha}/f_c = 0.6$ to 1.8. This implies that if dust is indeed clumped in the ISM of high-redshift galaxies such that the relative Ly$\alpha$ escape fraction can be as high as 1.8 times the UV escape fraction, we cannot differentiate between a universe which is either completely ionized or half neutral (or where 38–50 per cent of LAE Ly$\alpha$ radiation is transmitted through the IGM) or an $f_{\text{esc}}$ ranging between 5 and 50 per cent. This parameter space is much larger than that allowed for a homogeneous dust distribution, where matching to the observations requires $f_{\text{esc}} = 0.05$ and $\langle X_{HI} \rangle \leq 0.1$ ($\langle T_{\alpha}\rangle_{\text{LAE}} \geq 0.43$).
6 CONCLUSIONS

In this work, we couple state-of-the-art cosmological simulations run using GADGET-2 with a dust model and an RT code (PCRAsh) to build a physical model of \( z \approx 6.7 \) LAEs to simultaneously constrain the IGM reionization state, the escape fraction of H I ionizing photons and ISM dust distribution (homogeneous/clumped).

We start by validating the properties of the simulated galaxy population against observations of high-redshift \( (z \approx 6–8) \) LBGs. Identifying bound structures using the AHF, simulated galaxies which are complete in the halo mass function \( (M_\text{h} \geq 10^{12} \, M_\odot) \) contain a minimum of \( 4N \) gas particles \( (N = 40) \) and a minimum of \( 10 \) star particles are identified as the ‘resolved’ population. For each such resolved galaxy, we use the mass, age and metallicity of each of its star particles to build the composite spectra. We use a dust model (Dayal et al. 2010) that calculates the SNII dust enrichment depending on the entire SF history of a given galaxy, to obtain the associated escape fraction of UV photons. Once these calculations are carried out, galaxies with a dust-attenuated UV magnitude \( M_\text{UV} \approx -17 \) are identified as LBGs at \( z \approx 6–8 \). Comparing the predictions by the simulation against LBG observations, we find that the slope and amplitude of the dust-attenuated UV LFs are in good agreement with the data at \( z \approx 6, 7 \) while the UV LF at \( z \approx 8 \) requires no dust to match the observations, such that \( f_\text{c} \approx (0.5, 0.6, 1.0) \) at \( z \approx (6, 7, 8) \), averaged over all LBGs. The theoretical Schechter parameters are found to be \( \alpha = (-1.9 \pm 0.2, -2.0 \pm 0.2, -1.8 \pm 0.2) \) and \( M_\text{UV,*} = (-19.8 \pm 0.3, -19.7 \pm 0.2, -19.9 \pm 0.3) \) at \( z \approx (6, 7, 8) \), and are consistent with those inferred observationally (McLure et al. 2009, 2013; Bouwens et al. 2011). We also find that the theoretical LBG stellar mass functions, SMDs and sSFRs are in excellent agreement with the data at \( z \approx 6–8 \) (see Appendix A).

Once that the physical properties and dust enrichment of the simulated galaxy population have been validated against the mentioned observational data sets, we proceed to modelling LAEs. This requires further information on (a) the fraction of the H I ionizing photons produced by a galaxy that are absorbed by ISM H I \((1 - f_\text{esc})\) and contribute to the Ly\( \alpha \) emission line; the rest \( f_\text{esc} \) emerge out and contribute to reionization, (b) the relative effect of ISM dust on Ly\( \alpha \) and UV photons \((f_\text{dust} / f_\text{c})\), and (c) the level to which the IGM is ionized by the galaxy population \((\langle \chi_{\text{HI}} \rangle)\), in order to calculate the IGM Ly\( \alpha \) transmission. Since \( f_\text{esc} \) remains poorly constrained with proposed values ranging between 0.1 and 100 per cent (e.g. Ricotti & Shull 2000; Gnedin et al. 2008; Ferrara & Loeb 2013), we use five different values of \( f_\text{esc} = 0.05, 0.25, 0.5, 0.75, 0.95 \) to run the RT code (PCRAsh) in order to obtain various ‘reionization’ states of the simulated volume as it evolves from being fully neutral \((\langle \chi_{\text{HI}} \rangle \approx 1)\) to completely ionized \((\langle \chi_{\text{HI}} \rangle \approx 10^{-4})\); PCRAsh follows the time evolution of the ionization fractions (H I and He ii, He iii) and temperature given the spectra of the source galaxy population. Once these calculations are carried out, galaxies with \( L_\text{IV} \geq 10^{42} \, \text{erg s}^{-1} \) and EW \( \geq 20 \, \text{Å} \) are identified as LAEs; the only free parameter of the model \((f_\text{dust} / f_\text{c})\) is then fixed by matching the simulated LFs to the observations.

We start from the simplest case of considering the SNII produced dust to be homogeneously distributed in the ISM. The SNII
extinction curve yields $f_a/f_c = 0.68$. Using this model, we find that for a given $f_{esc}$, the IGM Ly$\alpha$ transmission increases with decreasing $\langle \chi_H \rangle$, with this increase being most important for the smallest galaxies; as $\langle \chi_H \rangle$ decreases, even small galaxies are able to ionize a large enough H II region around themselves to be visible as LAEs. Hence, the Ly$\alpha$ LF becomes steeper with decreasing $\langle \chi_H \rangle$ for any given $f_{esc}$ value. Further, for a given $\langle \chi_H \rangle$, although the ionization fields look very similar for different $f_{esc}$ values, the degree of ionization $\langle \chi_H \rangle$ in any cell increases with $f_{esc}$ due to an increase in the H I ionizing photon emissivity. This leads to a slight increase in $T_a$ with $f_{esc}$ for a given $\langle \chi_H \rangle$. However, this increase is more than compensated by the decrease in the intrinsic Ly$\alpha$ luminosity with increasing $f_{esc}$ (as less photons are available for ionizations in the ISM), as a result of which the Ly$\alpha$ LF decreases slightly in amplitude with $f_{esc}$ for a given $\langle \chi_H \rangle$. Finally, comparing simulated Ly$\alpha$ and UV LFs with observations, we find that for a homogeneous ISM dust distribution and $f_{esc} = 0.05$, we can constrain $\langle \chi_H \rangle \leq 0.1$ or $\langle T_a \rangle_{LAE} \geq 0.43$.

We also explore the scenario of dust being inhomogeneously distributed/clumped in the ISM of high-redshift galaxies, boosting up the ratio of $f_a/f_c$. For a given $\langle \chi_H \rangle$ value, an increase in $f_{esc}$ leads to a drop in the amplitude of the Ly$\alpha$ LF due to a decrease in $L_a^{\text{int}}$, as mentioned above. In the clumped dust scenario, this decrease can be compensated by an increase in $f_a$. For $\langle \chi_H \rangle \simeq 0.5$, $f_{esc}$ values as high as 0.5 can be reconciled with the data, given that $f_a/f_c$ increases from $\simeq 0.6$ to 1.8 as $f_{esc}$ increases from 0.05 to 0.5. We thus find a three-dimensional degeneracy between $\langle \chi_H \rangle$, $f_{esc}$ and $f_a/f_c$, such that a decrease in $L_a^{\text{int}}$ with increasing $f_{esc}$ can be compensated by a larger $T_a$ and $f_a/f_c$. Due to the model dependence (e.g. Ly$\alpha$ line profile, reionization topology) of the $\langle \chi_H \rangle$–$\langle T_a \rangle$ relation, we also rephrase our result by converting the $\langle \chi_H \rangle$ values to the corresponding mean transmission values for LAEs ($\langle T_a \rangle_{LAE}$). Within a $1\sigma$ error, we find that allowing for clumped dust, the data can be reproduced for a wide parameter space of $\langle T_a \rangle_{LAE} \simeq 0.38–0.50$ or $\langle \chi_H \rangle \simeq 0.5–10^{-4}$, $f_{esc} \simeq 0.05–0.5$ and $f_a/f_c \simeq 0.6–1.8$, i.e. if dust is indeed clumped in the ISM of high-redshift galaxies such that the relative Ly$\alpha$ escape fraction can be as high as 1.8 times the UV escape fraction, we cannot differentiate between a universe which is either completely ionized or half neutral or where on average 38–50 per cent of the Ly$\alpha$ radiation is transmitted, or has an $f_{esc}$ ranging between 5 and 50 per cent. We caution the reader that although the constraints in terms of $\langle T_a \rangle_{LAE}$ account for the model-dependent relation between $\langle \chi_H \rangle$ and $\langle T_a \rangle$, the value of $\langle T_a \rangle_{LAE}$ sensitively depends on the galaxies that are classified as LAEs for a given combination of $f_{esc}$, $\langle \chi_H \rangle$ and $f_a/f_c$.

We now discuss some of the caveats involved in this work. First, an enhancement of the escape fraction of Ly$\alpha$ photons with respect to continuum photons via the Neufeld effect (Neufeld 1991) in a clumpy ISM remains controversial: on the one hand, Hansen & Oh (2006) showed that such enhancement was possible if the Ly$\alpha$ photons encountered a certain number of ‘clumps’. On the other hand, Laursen et al. (2013) have shown that enhancing the ISM Ly$\alpha$ escape fraction requires very specific conditions (no bulk outflows, very high metallicity, very high density of the warm neutral medium and a low-density and highly ionized medium) that are unlikely to exist in any real ISM.

Secondly, as a consequence of simulating cosmological volumes, we are unable to resolve the ISM of the individual galaxies to be
able to model the Lyα line profile that emerges out of any galaxy. We have therefore assumed the emergent Lyα line to have a Gaussian profile with the width being set by the rotation velocity of the galaxy. However, several observational (Tapken et al. 2007; Yamada et al. 2012) and theoretical works (Verhamme et al. 2008; Jensen et al. 2013) have found the emerging Lyα line profile to be double peaked; this profile results in higher IGM Lyα transmission values compared to a Gaussian profile (Jensen et al. 2013). An increase in $T_{esc}$ due to such a double-peaked profile allows our theoretical LFIs to fit the observations with slightly lower $f_{esc}/f_0$ values.

Thirdly, we assume a constant escape fraction $f_{esc}$ for all galaxies. Although the value of $f_{esc}$ and its dependence on galaxy properties (such as the stellar mass) are only poorly known, recent work hints at an $f_{esc}$ that decreases with increasing mass (Paardekooper et al. 2011; Ferrara & Loeb 2013). If $f_{esc}$ is indeed higher for low-mass galaxies, the ionization topology would become more homogeneous with the H ii regions being built by low-mass (high-mass) galaxies being larger (smaller) than the constant $f_{esc}$ case. This would have two effects: on the one hand, the IGM Lyα transmission would be enhanced (decreased) for low-mass (high-mass) galaxies, leading to a steeper Lyα LF. On the other hand, due to its direct dependence on $f_{esc}$, the intrinsic Lyα luminosity would decrease (increase) for low-mass (high-mass) galaxies, leading to a flattening of the Lyα LF. The relative importance of these two effects is the subject of a work currently in preparation.

Fourthly, we assume that dust in high-redshift galaxies is solely produced by SNII. However, as shown by Valiante et al. (2014), AGB stars can start contributing to significantly, and even dominate, the IGM Lyα transmission values compared to a Gaussian profile (Jensen et al. 2013). An increase in $T_{esc}$ due to such a double-peaked profile allows our theoretical LFIs to fit the observations with slightly lower $f_{esc}/f_0$ values.

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APPENDIX A: COMPARING THE SIMULATIONS WITH LBG OBSERVATIONS

A1 Stellar mass functions and SMD

We build simulated LBG mass functions by summing up LBGs on the basis of their stellar mass, and dividing this by the width of the bin and the simulated volume; for consistency with observations, this calculation is carried out for all LBGs with $M_{\text{UV}} \leq -18$. As expected from the hierarchical model, small-mass systems are the most numerous, with the number density decreasing with increasing mass. Further, the mass function shifts to progressively lower masses with increasing redshifts, as fewer massive systems have had the time to assemble. Both trends can be seen clearly from Fig. A1: at $z \approx 6$, galaxies with $M_\ast \simeq 10^{8.5} M_\odot$ are two orders of magnitude more numerous as compared to more massive galaxies with $M_\ast \simeq 10^{10.5} M_\odot$. Secondly, while there are systems as massive as $10^{10.7} M_\odot$ in the simulated volume at $z \approx 6$, such systems had not the time to evolve by $z \approx 8$ where the most massive systems have $M_\ast \simeq 10^{11} M_\odot$. From the same figure, we see that the slope and amplitude of the simulated stellar mass functions are in agreement with the observations for $M_\ast \geq 10^{8.5} M_\odot$; this number marks the limit of our simulation resolution for galaxies containing at least 4N gas particles and 10 star particles, as a result of which, the number density drops below it.

![Figure A1. Stellar mass function for LBGs with $M_{\text{UV}} \leq -18$ at $z \approx 6$–8. The dotted (red), dashed (blue) and solid (green) lines represent the simulated stellar mass functions for $z = 6$, 7 and 8, respectively. The shaded areas denote the respective Poisson errors. Squares (circles) represent the observational stellar mass functions at $z \approx 6$ (7) inferred by González et al. (2011), corrected for completeness but not for dust.](https://example.com/figureA1)

![Figure A2. Total SMD for LBGs with $M_{\text{UV}} \leq -18$. Filled black points represent the simulated SMDs; Poissonian errors are too small to be visible on the plot. The other symbols show the observed SMD values inferred by González et al. (2011, empty red squares), Labbé et al. (2010b, empty green circles), Labbé et al. (2010a, empty green circles) and Stark et al. (2013, empty blue triangles).](https://example.com/figureA2)
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Figure A3. sSFR for LBGs with $M_{UV} \leq -18$. Filled black points represent the simulated sSFRs; Poissonian errors are too small to be visible on the plot. Observed sSFR values plotted have been taken from González et al. (2010, empty red squares), Stark et al. (2009, empty green triangles), Yabe et al. (2009, empty magenta triangles), Schaerer & de Barros (2010, empty orange circles) and Stark et al. (2013, empty blue triangles).

As a result of the stellar mass functions shifting to progressively lower masses and number densities with increasing redshift (see Fig. A1), the total SMD in the simulated volume decreases with increasing redshift, as shown in Fig. A2, falling by a factor of about 40 from $10^7 \, M_\odot \, Mpc^{-3}$ at $z \sim 6$ to $10^{4.4} \, M_\odot \, Mpc^{-3}$ at $z \sim 9.5$. As expected from the agreement between the simulated stellar mass functions and those inferred observationally by González et al. (2011), the simulated SMD values are also in agreement with the observations. However, as pointed out by Schaerer & de Barros (2010) and Stark et al. (2013), including the effects of nebular emission can lead to a decrease in the observationally inferred stellar mass values; this effect causes a slight discrepancy between the SMD values obtained from our model and those inferred by Stark et al. (2013) at $z \sim 6$, as shown in Fig. A2.

A2 Specific star formation rates

The specific star formation rate (sSFR) is an excellent indicator of the current SFR compared to the entire past SF history of the galaxy. This quantity also has the advantage that it is relatively independent of assumptions regarding the IMF, metallicity, age and dust content since both the SFR and stellar mass are affected similarly by...
these parameters. Recently, a number of observational groups have suggested that the sSFR settles to a value consistent with $2-3 \text{ Gyr}^{-1}$ at $z \approx 3-8$ (Stark et al. 2009; González et al. 2010; McLure et al. 2011; Labbé et al. 2013; Stark et al. 2013). This result is quite surprising given that theoretically, the sSFR is expected to trace the baryonic infall rate that scales as $(1+z)^{2.25}$ (Neistein & Dekel 2008). However, Labbé et al. (2013) and Stark et al. (2013) have shown that at least a part of this discrepancy can be accounted for by the addition of nebular emission lines; indeed, the sSFR can rise by a factor of about 5 between $z \approx 2$ and $z \approx 7$ when nebular emission is taken into account.

Physically, the least massive galaxies tend to have the highest sSFR: as a result of their low $M_*$ values, even a small amount of SF can boost their sSFR compared to that of more massive systems (see also Dayal & Ferrara 2012; Dayal et al. 2013). Since the mass function progressively shifts to lower masses with increasing redshifts, and smaller mass galaxies have larger sSFR values, the sSFR rises with increasing redshift (see Fig. A3), from sSFR $\approx 5 \text{ Gyr}^{-1}$ at $z \approx 6$ to sSFR $\approx 12 \text{ Gyr}^{-1}$ at $z \approx 9.5$, in accordance with other theoretical results (Biffi & Maiolino 2013; Dayal et al. 2013; Salvaterra et al. 2013). We note that in the redshift range of overlap ($z \approx 6-7$), the theoretically inferred sSFR values are in agreement with observations.

**APPENDIX B: COSMIC VARIANCE**

In Fig. A4, we show the cosmic variance associated with the simulated Lyα LFs. The cosmic variance is estimated by computing the Lyα LFs for eight sub-volumes of our simulation volume, such that each sub-volume is $1.87 \times 10^5 \text{ Mpc}^3$ and thus comparable to the volume observed by Kashikawa et al. (2011). As $\langle \chi_{\text{HI}} \rangle$ evolves from an IGM which is predominantly neutral at $\langle \chi_{\text{HI}} \rangle \approx 0.75$ to one wherein reionization is complete ($\langle \chi_{\text{HI}} \rangle \approx 10^{-4}$), the value of $T_{\alpha}$ increases in all sub-volumes, leading to a decrease in the cosmic variance at the faint end of the LF; the variance at the bright end arises due to few objects being massive/luminous enough to occupy these bins in any given sub-volume.

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