Lyman $\alpha$ emitters in cosmological simulations – I. Lyman $\alpha$ escape fraction and statistical properties at $z = 3.1$

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ABSTRACT

We use very large cosmological smoothed particle hydrodynamics simulations to study the properties of high-redshift Lyman $\alpha$ emitters (LAEs). We identify star-forming galaxies at $z = 3.1$ in a cosmological volume of 100 $h^{-1}$ Mpc on a side. We develop a phenomenological model of absorption, scattering and escape of Lyman $\alpha$ photons on the assumption that the clumpiness of the interstellar medium in a galaxy is correlated with the larger scale substructure richness. The radiative transfer effect proposed by Neufeld allows a large fraction of Lyman $\alpha$ photons to escape from a clumpy galaxy even if it contains a substantial amount of dust. Our model reproduces, for the first time, all of the following observed properties of LAEs at $z = 3.1$: the angular correlation function, ultraviolet (UV) and Lyman $\alpha$ luminosity functions and the equivalent width distribution. A simple model that takes only dust absorption into account fails in reproducing LAEs that are also bright in UV, suggesting that the kind of effect we consider is needed. Our model predicts a bimodal age distribution for LAEs. Most of the galaxies with large Lyman $\alpha$ equivalent widths are young, whereas there are also old, massive and dusty LAEs, similar to recently found high-redshift LAEs. The large LAEs have escape fractions of Lyman $\alpha$ photons of $f_{\text{esc}} \sim 0.05–0.1$.

Key words: galaxies: evolution – galaxies: formation – galaxies: high redshift – galaxies: Ly$\alpha$ emitters – large-scale structure of Universe.

1 INTRODUCTION

A population of star-forming galaxies at high redshifts is characterized by their strong Lyman $\alpha$ line emission. Such Ly$\alpha$ emitters (LAEs) have been found at various redshifts by narrow-band surveys using 8–10 m class telescopes (Hu, Cowie & McMahon 1998; Hu, McMahon & Cowie 1999; Hu et al. 2002; Kodaira et al. 2003; Shimasaku et al. 2003, 2006; Hayashino et al. 2004; Matsuda et al. 2004, 2005; Ouchi et al. 2004, 2005, 2008; Taniguchi et al. 2005; Iye et al. 2006).

It is generally thought that the strong Ly$\alpha$ emission physically originates from star-forming regions (H II regions) in a young starburst galaxy. Some LAEs have very large equivalent widths (EW$_{Ly\alpha}$) exceeding 400 Å, which is difficult to explain with ordinary stellar population synthesis models (e.g. Charlot & Fall 1993; Schaerer 2003). Alternative physical models include cooling radiation from a primordial collapsing gas (Haiman, Spaans & Quataert 2000; Fardal et al. 2001), from a galactic wind-driven shell (Taniguchi & Shioya 2000) and from supernova remnants (Mori, Umemura & Ferrara 2004; Mori & Umemura 2006).

Recent large LAE surveys provided an array of statistical properties of LAEs such as the Ly$\alpha$ luminosity function, two-point angular correlation function and the evolution of them. The observations generally suggest that LAEs are not simply a subset of star-forming galaxies. Indeed, theoretical models proposed so far do not fully explain the observed properties. In particular, reproducing very large equivalent widths of some bright LAEs appears to be challenging. Ly$\alpha$ photons are easily absorbed by dust and thus it is naïvely expected that an LAE is a very young and dust-free galaxy. While some observations and theoretical studies actually support the notion (Gawiser et al. 2006, 2007; Mori & Umemura 2006; Shimizu, Umemura & Yonehara 2007), more recent multiwavelength observations of LAEs in optical, infrared and submillimetre suggest that there are LAEs that are indeed old and dusty (Finkelstein et al. 2007, 2009c; Matsuda et al. 2007; Lai et al. 2008; Uchimoto et al. 2008; Tamura et al. 2009; Ono et al. 2010). Interestingly, such a population increases with decreasing redshift (Nilsson et al. 2009). There is even evidence that some submillimetre galaxies show strong Ly$\alpha$ emission (Smail et al. 2004). The existence of a substantial amount of dust appears incompatible with strong Ly$\alpha$ emission. There must be a physical mechanism for Ly$\alpha$ photons to escape from such dusty galaxies.

There have been a number of theoretical studies on the population of LAEs. Nagamine et al. (2010) study a stochastic model where a
galaxy goes through LAE phase occasionally. Shimizu & Umemura (2010) argue that an old evolved galaxy can become a LAE as a consequence of delayed gas accretion. Their model assumes that the delayed starburst occurs at the outskirts of a galaxy so that Ly$\alpha$ photons can escape easier than those emitted from the central region. Dayal et al. (2009), Dayal, Ferrara & Saro (2010) and Dayal, Maselli & Ferrara (2011) perform cosmological simulations to study the ultraviolet (UV) and Ly$\alpha$ luminosity functions. Dayal et al. (2011) further calculate the neutral hydrogen fraction at $z = 5.7$ by using a combination of their LAE formation model and radiation transfer calculations of hydrogen reionization. McQuinn et al. (2007) and Mesinger & Furlanetto (2008) study the effect of the mean neutral hydrogen fraction of the intergalactic medium (IGM) on the Ly$\alpha$ luminosity function and on the spatial distribution of simulated LAEs. Zheng et al. (2011) study the clustering properties of LAEs using a cosmological reionization simulation with detailed Ly$\alpha$ radiative transfer calculations.

Semi-analytic models are also used to study the statistical properties of LAEs. Dijkstra & Wyithe (2007) propose a model in which LAEs undergo a burst of very massive star formation, yielding large Ly$\alpha$ equivalent width. De Lelliou et al. (2006) and Orsi et al. (2008) adopt a top-heavy IMF when starburst occurs. They show that the Ly$\alpha$ luminosity increases at starburst, whereas Kobayashi, Totani & Nagashima (2007, 2010) consider the effect of galaxy-scale outflows on the Ly$\alpha$ escape fraction.

It has been suggested that gas motions in and around galaxies can significantly affect the absorption of Ly$\alpha$ photons (Kunth et al. 1998; Dijkstra, Lidz & Wyithe 2007; Atek et al. 2008; Verhamme et al. 2008; Dijkstra & Wyithe 2010; Zheng et al. 2010a,b). Strong galactic winds from Ly$\alpha$ emitting galaxies are indeed found in the local universe (Lequeux et al. 1995; Kunth et al. 1998, 2003; Mas-Hesse et al. 2003; Keel 2005), as well as for high-z Lyman break galaxies (LBGs) with strong Ly$\alpha$ emission (Pettini et al. 2002; Bower et al. 2004; Wilman et al. 2005; Shapley et al. 2006; Frye et al. 2007; Pentericci et al. 2007; Tapken et al. 2007). An important effect caused by strong gas flows is that the line centre of Ly$\alpha$ photons is shifted. Then Ly$\alpha$ photons can escape more easily from the central galaxy. However, it is unlikely that all the LAEs blow strong galactic winds because only a small fraction of high-redshift galaxies shows the signature of strong outflow (McLinden et al. 2010). The local and large-scale gas motions also modify the line shape of Ly$\alpha$ and the Ly$\alpha$ luminosity function (Atek et al. 2009; Dijkstra & Wyithe 2010).

Laursen, Sommer-Larsen & Razoumov (2011) used cosmological simulations to show that the effect of IGM opacity to Ly$\alpha$ photons is non-negligible even at low redshifts. They found that the average value of transmission at $z = 3.5$ is 0.77 with substantial scatters for individual galaxies. Although the resolution of currently available simulations is still limited and thus they cannot directly resolve the structure of the interstellar medium (ISM), it is clear that gas motions, at large scales as well as around individual galaxies, critically affects Ly$\alpha$ photon transfer.

It is important to consider another physical process for massive dusty galaxies to be bright LAEs. Neufeld (1991) proposed an important effect for Ly$\alpha$ transfer. In a clumpy, multiphase ISM, dust is locked up in small cold clouds. Ly$\alpha$ photons can then escape from the clumpy ISM easier than continuum photons because Ly$\alpha$ photons, having a very large scattering cross-section, are preferentially scattered at the surface of the clouds. On the other hand, UV continuum photons are easily absorbed by dust. Neufeld’s model can explain not only the existence of Ly$\alpha$ emission from dusty galaxies but also the observed high equivalent widths (Hansen & Oh 2006; Kobayashi et al. 2007, 2010; Finkelstein et al. 2008, 2009a,b). Scarletta et al. (2009) show that it is difficult to reproduce the line ratio of Ly$\alpha$ to H$\alpha$ if uniform mixing is assumed for the photon sources and dust. They argue that ‘clumpy’ dust distribution may explain the observational result. Clearly it is important to incorporate the effect of dust distribution in modelling LAEs.

In this paper, we study the statistical properties of LAEs at $z = 3.1$. We perform large cosmological hydrodynamic simulations for the standard $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology. Our simulations follow star formation, supernova feedback and metal enrichment. For galaxies identified in our cosmological simulation, we calculate the spectral evolution and dust extinction. We utilize the internal structure of dark haloes to calculate the escape probability of Ly$\alpha$ photons. Then we can directly calculate the UV luminosity function, the Ly$\alpha$ luminosity function, the EW$_{Ly\alpha}$ distribution and the spatial distribution of simulated galaxies.

Throughout this paper, we adopt the $\Lambda$CDM cosmology with the matter density $\Omega_M = 0.27$, the cosmological constant $\Omega_\Lambda = 0.73$, the Hubble constant $h = 0.7$ in units of $H_0 = 100$ km $\text{s}^{-1} \text{Mpc}^{-1}$, the baryon density $\Omega_b = 0.046$ and the matter density fluctuations are normalized by setting $\sigma_8 = 0.81$ (Spergel et al. 2003). All magnitudes are expressed in the AB system, and all Ly$\alpha$ EW$_{Ly\alpha}$ values in this paper are in the rest frame.

2 THEORETICAL MODEL

2.1 Numerical simulations

Our simulation code is based on an early version of the Tree-PM smoothed particle hydrodynamics (SPH) code GADGET-3 which is a successor of Tree-PM SPH code GADGET-2 (Springel 2005). We simulate $N = 2 \times 640^3$ particles in a comoving volume of $100 h^{-1} \text{Mpc}$ on a side. The mass of a dark matter particle and that of a gas particle are $2.41 \times 10^8$ and $4.95 \times 10^9 h^{-1} \text{M}_\odot$, respectively.

Physical processes such as star formation and feedback are implemented as in Okamoto, Nemmen & Bower (2008), Okamoto & Frenk (2009) and Okamoto et al. (2010). In particular, our simulations employ a new galactic wind model in which the initial velocity of a wind particle is proportional to the local velocity dispersion of the dark matter particles. This is motivated by observations that suggest large-scale outflows have velocities that scale with the circular velocity of their host galaxies (Martin 2005). As a proxy for host halo’s circular velocity, which is not easily calculated on-the-fly, we use the local one-dimensional velocity dispersion, determined from neighbouring dark matter particles. Okamoto et al. (2010) found that this quantity, $\sigma$, is strongly correlated with the maximum circular velocity of host (sub-) haloes, $v_{\text{max}}$, and the relation between these quantities does not evolve with redshift. This prescription results in a wind speed that increases as a halo grows and hence a wind mass loading [wind mass per unit star formation rate (SFR)] is highest at early times (or in small haloes). This scaling has been shown to reproduce the physical properties of the Local Group satellites (Okamoto & Frenk 2009; Okamoto et al. 2010).

Our simulations include the time-evolving photoionization background (Haardt & Madau 2001), metallicity-dependent gas cooling and photoheating (Wiersma, Schaye & Smith 2009), supernovae feedback and chemical enrichment (Okamoto et al. 2005, 2008). We use metallicity-dependent stellar lifetimes and chemical yields (Portinari, Chiosi & Bressan 1998; Marigo 2001). The details of these processes are found in the above references. Here we give a brief summary. Each SPH particle can spawn a new star particle when the particle satisfies a set of standard criteria for star

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formation. A star particle carries its properties such as mass, formation time and metallicity. As in ordinary galaxy formation simulations, a star particle represents a cluster of stars with a range of stellar masses. We assume the Salpeter initial mass function (IMF) with mass range 0.1 to 120 M⊙. Our simulation follows the chemical evolution of the interstellar gas. We assign the gas metallicity to each newly formed star particle with the range from 0.01 to 10 Z⊙, where Z⊙ is the solar metallicity. We calculate the spectral energy distribution (SED) of each star particle using the population synthesis code PEGASE (Fioc & Rocca-Volmerange 1997). We then sum the individual SEDs to obtain the total intrinsic SED of a simulated galaxy.

We use a runs-of-friends (FoF) group finder (Davis et al. 1985) to locate groups of stars, i.e. galaxies. We also identify substructures (subhaloes) in each FoF group using SUBFIND algorithm developed by Springel et al. (2001). For the identified galaxies, we calculate the intrinsic Lyα luminosities using PEGASE. In PEGASE, two-thirds of ionizing photons are converted to Lyα photons under the assumption of the case B recombination. Fig. 1 shows the time evolution of the intrinsic EW_{Lyα} for different metallicities. The solid, dashed, dashed–dot and dotted lines represent EW_{Lyα}(t) with 0.01, 0.1, 1 and 10 Z⊙, respectively. Large EW_{Lyα} (>200 Å) is found only for young, low-metallicity stars. We will discuss the ages of LAEs in Section 3.5. Finally, we need to include the effect of dust extinction on UV continuum and Lyα emission. This is the key component of our model. We will describe the details in the next subsection.

2.2 Model description for dust absorption

We calculate the SED and the Lyα luminosity for individual galaxies identified in our cosmological simulation. In order to compare our model predictions directly with observational data, we need to include the effect of dust absorption. We first assume that the dust mass is given by

\[ M_d = 0.01M_g \frac{Z}{Z⊙} \]

where \( M_d, M_g \) and \( Z \) are the total dust mass, the total gas mass and metallicity of a simulated galaxy, respectively (see e.g. Draine et al. 2007). Here the metallicity \( Z \) of a galaxy is calculated from the metallicities of gas particles. We further assume that the galaxies are roughly spherical; we use only one length scale, the effective radius, to evaluate the optical depth. We calculate the optical depth \( \tau_d(\lambda) \) for UV continuum photons as

\[ \tau_d(\lambda) = \frac{3\Sigma_d}{4a_d s} \]

where \( a_d \) and \( s \) are the typical size of dust grains and the material density of dust grains, respectively. We adopt the standard choice of \( a_d = 0.1 \mu m \) and \( s = 2.5 \times 10^3 \text{g cm}^{-3} \) (Todini & Ferrara 2001; Nozawa et al. 2003). The dust surface mass density \( \Sigma_d \) is

\[ \Sigma_d = \frac{M_d}{\pi r_d^2} \]

where \( M_d \) and \( r_d \) are the total dust mass (50 per cent of metal mass) and the effective radius of the galaxy, respectively. The effective radius \( r_d \) is a fraction of the virial radius and is given by \( f_d r_{vir} \) with a scale parameter \( f_d \). We set \( f_d = 0.13 \) such that the UV luminosity function matches the observed UV luminosity function of LBGs around \( z \sim 3 \) (see Fig. 2). The escape fraction of UV continuum photons \( f_{\text{cont}}(\lambda) \) is then calculated as

\[ f_{\text{cont}}(\lambda) = \frac{1 - \exp(-\tau_d(\lambda))}{\tau_d(\lambda)} \]

We use the dust optical constant \( Q \) as a function of wavelength given in Draine & Lee (1984). We also calculate the IGM absorption at the blue side of 1216 Å following Madau (1995). Fig. 2 shows the UV luminosity function of the simulated galaxies. Solid line is our simulation result at \( z = 3.1 \). The points with error bars represent a compilation of several observational results (Arnouts et al. 2005, Sawicki & Thompson 2006 and Reddy & Steidel 2009).
et al. 2005; Sawicki & Thompson 2006; Reddy & Steidel 2009). Our model reproduces the observed luminosity function reasonably well, although it slightly overpredicts the number of faint galaxies.

A crucial quantity in our model is the effective optical depth of Lyα line, \( \tau_{Ly\alpha} \). We employ two models to calculate the effective optical depth. A simplest assumption would be to set

\[
\tau_{Ly\alpha}^{abs} = c_{abs}T_d,
\]

where \( c_{abs} \) is a constant parameter. Then, the escape fraction of Ly\( \alpha \) photons \( f_{Ly\alpha}^{abs} \) is given by

\[
f_{Ly\alpha}^{abs} = \frac{1 - \exp(-\tau_{Ly\alpha}^{abs})}{\tau_{Ly\alpha}^{abs}}.
\]

We call this model as pure absorption model. Essentially, dust is treated as a pure absorber of Ly\( \alpha \) photons in this model (e.g. Dayal et al. 2009, 2010, 2011). Ly\( \alpha \) photons cannot easily escape from dusty galaxies which have a large effective optical depth.

The second model, which we propose in the present paper, is motivated by the multiphase ISM model of Neufeld (1991). In a clumpy ISM, Ly\( \alpha \) photons are scattered mostly at the surface of cold clumps before they are absorbed by dust. A large fraction of Ly\( \alpha \) photons can then escape from a clumpy ISM through multiple scatters. The key quantity here is the overall clumpiness of the ISM in a galaxy. Since our cosmological simulation does not resolve the fine structure of the ISM, we need to estimate the clumpiness of the ISM in some way. It is probably reasonable to expect that the ISM structure is well developed in a massive galaxy which itself has rich substructures. We make an assumption that the clumpiness of the ISM has a correlation with the larger scale internal structure of the host halo. In practice, we use the number of subhaloes (satellites) \( N_{sub} \) of the galaxy as a measure of its ‘clumpiness’. We introduce the clumpiness factor \( S \), which depends on \( N_{sub} \), and express the effective optical depth to Ly\( \alpha \) photons as

\[
t_{Ly\alpha} = c_{sub}S T_d,
\]

where \( c_{sub} \) is a normalization constant. For simplicity, we assume the clumpiness factor is expressed as a power law:

\[
S = N_{sub}^\alpha.
\]

After some experiments, we find that setting \( \alpha = -0.6 \) works remarkably well, reproducing nearly all the important observational data, as will be shown in the following sections. We call this model the substructure model. The escape fraction of Ly\( \alpha \) photons \( f_{Ly\alpha}^{sub} \) in this model is given by

\[
f_{Ly\alpha}^{sub} = \frac{1 - \exp(-\tau_{Ly\alpha}^{sub})}{\tau_{Ly\alpha}^{sub}}.
\]

The combination of equations (8) and (9) effectively yields a larger escape fraction for a dusty but ‘clumpy’ galaxy. Finally, we fix the normalization constants in the two models, \( c_{abs} \) and \( c_{sub} \), by matching the number density of simulated LAEs with the observed number density \( n_{LABS} \sim 5 \times 10^{-4} \text{Mpc}^{-3} \) (Ouchi et al. 2008). We set \( c_{abs} = 8.8 \) and \( c_{sub} = 12.1 \).

It is generally necessary to consider Ly\( \alpha \) absorption by the IGM. Because we focus on the statistical properties of LAEs at \( z = 3.1 \) in the present paper, we effectively assume that the IGM is nearly fully ionized and that Ly\( \alpha \) transmission is unity through the IGM (see, however, e.g. Laursen et al. 2011 for realistic values of transmission). We identify simulated galaxies which satisfy \( EW_{Ly\alpha} > 30 \text{ Å} \) and \( L_{Ly\alpha}^{obs} > 1.0 \times 10^{42} \text{erg s}^{-1} \) as LAEs. We note that it is difficult to estimate accurate \( EW_{Ly\alpha} \) with only photometric observations. There remain uncertainties in \( EW_{Ly\alpha} \) determined without spectroscopic observations, as stated in Ouchi et al. (2008). In this study, we set the threshold of \( EW_{Ly\alpha} \) by noting the lowest value of fig. 25 in Ouchi et al. (2008).

### 3 Result

#### 3.1 Spatial distribution of simulated LAEs

Fig. 3 shows the projected distribution of the LAEs at \( z = 3.1 \) in the simulation volume of 100 comoving \( h^{-1} \text{Mpc} \) on a side. The point size represents the Ly\( \alpha \) luminosity of each galaxy. Luminous LAEs are shown by large and green points. The overall distribution appears quite similar in the two models, with LAEs approximately tracing the underlying matter distribution. The luminous LAEs are clustered more strongly in the substructure model.

We quantify the spatial distribution of the simulated LAEs by calculating the two-point angular correlation function (ACF). Our simulation volume is large enough to have six independent regions of the size of Subaru/XMM-Newton Deep Field (SXDF) survey (Ouchi et al. 2008). We calculate the ACFs for each subboxes and calculate the average. Fig. 4 shows the ACFs for our simulated LAEs. The ACF of the observed LAEs of Ouchi et al. (2008), Gawiser et al. (2006) and Hayashino et al. (2004) is also shown in the figure. Both of our models reproduce the observational result well. The LAEs at \( z \sim 3.1 \) are typically hosted by dark haloes with mass of \( \sim 10^{11} \text{M}_\odot \).

#### 3.2 Ly\( \alpha \) luminosity functions

In Fig. 5, we compare the Ly\( \alpha \) luminosity functions with the observational data at \( z = 3.1 \). The pure absorption model (left-hand panel) does not produce very bright LAEs with \( L_{Ly\alpha} > 10^{43.5} \text{erg s}^{-1} \). In both our models, the intrinsic Ly\( \alpha \) luminosity of a galaxy is proportional to its SFR, and thus the ‘intrinsically’ bright LAEs are hosted typically by massive haloes. However, such massive galaxies are also aged and dusty. Because of the strong dust absorption of Ly\( \alpha \) photons (see equation 5), dusty star-forming galaxies do not appear as LAEs in the pure absorption model. Note also that the pure absorption model assumes uniform mixing of Ly\( \alpha \) photon sources and dust (see equations 6 and 9). Scarlata et al. (2009) argue, based on recent observations of LAEs at \( z = 0.3 \), that dust is likely distributed in a clumpy manner.

Our substructure model, on the other hand, shows a better agreement with the observational data. Dusty, aged and massive galaxies are hosted by haloes with many subhaloes. We assume that the evolved galaxies have also a more complex ISM structure, where Ly\( \alpha \) photons can escape easily because of the Neufeld effect. In our substructure model, even aged and dusty galaxies appear as bright LAEs and the resulting luminosity function matches well the observation at all luminosities. Fig. 6 shows the escape fraction of Ly\( \alpha \) photons as a function of the host halo mass. The escape fraction decreases with increasing halo mass in both the models. However, in pure absorption model, the escape fraction is essentially zero for massive galaxies because the galaxies are physically large and dusty (see equations 5 and 6). The substructure model predicts that the Ly\( \alpha \) escape fraction of massive galaxies is \( f_{esc} \sim 0.05–0.1 \), with a substantial dispersion.

The relatively large escape fractions for massive galaxies make the substructure model more successful in reproducing the observed luminosity function.
Figure 3. The large-scale distribution of the simulated LAEs. The left- and right-hand panels show LAEs in the pure absorption model and those in the substructure model, respectively. The point size is scaled with the Ly$\alpha$ luminosity of each galaxy so that luminous galaxies appear as large points. The smallest and biggest points correspond to LAEs with $10^{42} \leq L_{\text{Ly}\alpha} \leq 10^{42.2}$ erg s$^{-1}$ and $L_{\text{Ly}\alpha} \geq 10^{43}$ erg s$^{-1}$, respectively. The colour bar also shows the Ly$\alpha$ luminosities of the simulated LAEs.

Figure 4. The two-point ACF. The solid line with error bars represents the substructure model and the pure absorption model, respectively. Filled circle, filled square and filled triangle show the ACF of observed LAEs in Ouchi et al. (2008), Gawiser et al. (2006) and Hayashino et al. (2004).

3.3 $M_{\text{UV}}$–$\text{EW}_{\text{Ly}\alpha}$ distribution

Fig. 7 shows the distributions of our simulated LAEs in the $M_{\text{UV}}$–$\text{EW}_{\text{Ly}\alpha}$ plane at $z = 3.1$. The dots represent our simulated LAEs, and the points with error bars are the observational data (Ouchi et al. 2008). In pure absorption model, there are no UV bright LAEs ($M_{\text{UV}} < -20$) in this plot. UV bright objects are massive and already dusty at $z = 3.1$, as discussed in the previous subsection. Our substructure model yields many UV bright LAEs with $M_{\text{UV}} < -20$. However, even the substructure model does not produce the UV bright LAEs with large $\text{EW}_{\text{Ly}\alpha}$ (>100 Å). The geometrical effect on Ly$\alpha$ transfer appears to be insufficient, as indeed indicated by the recent observations of Kornei et al. (2010). It may be necessary to include the effect of galactic outflow to explain the UV-bright LAEs with large equivalent widths, such as a few outliers found in Fig. 7.

3.4 UV luminosity function of simulated LAEs

An outstanding difference between our two models is the existence of UV bright LAEs ($M_{\text{UV}} < -20$). To further quantify this point, we calculate the UV luminosity function of the simulated LAEs and compare our models with the observational result. We employ two thresholds for equivalent widths, $\text{EW}_{\text{Ly}\alpha}^{\text{th}} > 30$ and $\geq 60$ Å. Kobayashi et al. (2010) showed that the shape of the UV luminosity
Figure 5. The Lyα luminosity function for the pure absorption model (left) and for the substructure model (right). We compare the model predictions with the observational data of Ouchi et al. (2008) with error bars. The filled circle marked an open square indicates LAE with active galactic nucleus (AGN).

Figure 6. The escape fraction of Lyα photons for the pure absorption model (left) and for the substructure model (right).

function of LAEs is sensitive to the threshold value. Fig. 8 shows the UV luminosity functions. The solid and dashed lines show the UV luminosity function with $\text{EW}_{\text{Ly} \alpha} > 30$ and $> 60$ Å, respectively. The solid points with error bars are observational result (Ouchi et al. 2008). Clearly, the pure absorption model fails in reproducing the observational data regardless of the threshold value of $\text{EW}_{\text{Ly} \alpha}$. The substructure model prediction matches the observational result well for whole UV magnitude range. Note also that the number of UV bright LAEs increases with decreasing the threshold value of $\text{EW}_{\text{Ly} \alpha}$.

### 3.5 Lyα equivalent width distribution

In Fig. 9, we compare the rest-frame Lyα equivalent widths of simulated LAEs (histograms) with the observational data (solid line with error bars, dashed line and dash-dot line). The observed distribution is approximately reproduced. It is important to note that our selection criterion of LAEs ($\text{EW}_{\text{Ly} \alpha} > 30$ Å) is different from Ouchi et al. (2008) ($\text{EW}_{\text{Ly} \alpha} > 64$ Å). We use the lower, conservative threshold because the observational estimate of $\text{EW}_{\text{Ly} \alpha}$ itself is subject to some uncertainties when only photometric data are used. Fig. 9 clearly shows that our models produce many LAEs with $\text{EW}_{\text{Ly} \alpha} < 50$ Å, whereas there are few such samples in the observational data. If we discard LAEs with $\text{EW}_{\text{Ly} \alpha} < 64$ Å, the apparent agreement with the observational result becomes better.

The fraction of small $\text{EW}_{\text{Ly} \alpha}$ LAEs in the substructure model is larger than that in the pure absorption model. On the other hand, the fraction of LAEs with $\text{EW}_{\text{Ly} \alpha} > 300$ Å is nearly the same for both the models. This is because most of the LAEs with large $\text{EW}_{\text{Ly} \alpha}$ are young and less dusty, for which details of Lyα transfer models do not matter much.

Both of our models predict that the fraction of large $\text{EW}_{\text{Ly} \alpha}$ LAEs ($\text{EW}_{\text{Ly} \alpha} > 300$ Å) is larger than the observational result (Ouchi et al. 2008). Because such large $\text{EW}_{\text{Ly} \alpha}$ LAEs are faint in UV.
3.6 Age distribution of simulated LAEs

Finally, we show the age distribution of simulated LAEs in Fig. 10. We calculate the mass weighted mean of the stellar ages for individual galaxies. In the pure absorption model, the number of simulated LAEs decreases with increasing age. Simply, aged galaxies are not LAEs. The LAEs in the substructure model show clearly a bimodal distribution. Recently formed galaxies are young LAEs, whereas massive, dusty galaxies with $t_{\text{age}} > 4 \times 10^9$ yr can also appear as bright LAEs. The latter population is indeed found recently by Finkelstein et al. (2009a).

4 CONCLUSIONS AND DISCUSSION

We study a number of observed properties of LAEs using a large cosmological hydrodynamic simulation. The simulation follows the formation and evolution of star-forming galaxies by employing new feedback models of Okamoto et al. (2010). We develop a novel model in which Ly$\alpha$ photons can escape from a massive, dusty galaxy if the ISM is clumpy. The idea is motivated by the multiple scattering and escape of Ly$\alpha$ photons originally proposed by Neufeld (1991).

Our physical model of LAEs reproduces not only the Ly$\alpha$ luminosity function but also $M_{\text{UV}}$–EW$_{\text{Ly}\alpha}$ distribution, the UV...
luminosity function of LAEs, the equivalent width distribution and
the angular two-point correlation function at $z = 3.1$. It is the first
theoretical model that successfully reproduces all these observa-
tional results using cosmological hydrodynamic simulations. In-
terestingly, the model predicts the Ly$\alpha$ escape fraction is roughly
constant for the massive LAEs. Massive, dusty and aged galaxies
appear as bright LAEs, as is consistent with recent observa-
tions. Contrastingly, the pure absorption model fails in reproducing
some observational results. Especially, the model reproduces no UV
bright LAEs ($M_{\text{UV}} < 20$), being inconsistent with recent observa-
tions. We argue that the kind of effect to enhance Ly$\alpha$ photon escape
from massive dusty galaxies is necessary for modelling LAEs. Sim-
ilar conclusion was obtained by Scarlata et al. (2009) for $z = 0.3$
LAEs. It is important to note that, in our models, the opacity to Ly$\alpha$
photons itself is large. For example, the value of the combination of
c$\text{sub}(=12.1)$ and $S$, namely $c_{\text{sub}}S$, in equation (7) is larger than unity
for most of the galaxies. Clearly, Ly$\alpha$ photons do not necessarily
escape easier from a dusty galaxy than UV continuum photons,
even if the galaxy has clumpy structures. Our results suggest that
Ly$\alpha$ photons also suffer from substantial dust attenuation in a dusty
LAE. Interestingly, this view is supported by recent observations
by Hobby–Eberly Telescope Dark Energy Experiment (HETDEX;
Blanc et al. 2011).

It is interesting to ask if the Ly$\alpha$ escape fraction can be described
as a simpler function of galaxy mass. In our simulation, the sub-
structure abundance of simulated galaxies roughly scales with their
host halo mass, although with substantial dispersions. The disper-
sion may also be important to reproduce some observational results.
To explicitly test the idea, we have employed a simpler model in
which the Ly$\alpha$ escape fraction is a function of host halo mass so
that the escape fraction approximately matches to the mean escape
fraction of our substructure model for a given halo mass. We have
also included random scatter with the same dispersions. We have found that this simple model fails in reproducing the M_{UV}–EW_{Ly\alpha} distribution and ACF. The simple model boosts the Ly\alpha luminosity too much and cannot explain the existence of UV-bright LAEs with low equivalent widths (see Fig. 7). Furthermore, in the simple model, massive galaxies are identified selectively as LAEs. Consequently, the strength of ACF becomes large, although it is still within the scatter of the current observational data. Overall, we conclude that the internal structure of a host halo is an important factor to determine its appearance as a LAE. Interestingly, Charlot & Fall (1993), Kunth et al. (1998) and Atek et al. (2008, 2009) argue that a large scatter of Ly\alpha emission versus metallicity correlation may be caused by the structure of the ISM.

In the present paper, we have focused on the physical properties of LAEs at a particular redshift of z = 3.1 where an array of observations of LAEs is available. According to very recent observations, the fraction of old population in observed LAEs increases with decreasing redshift, whereas the escape fraction of Ly\alpha emission becomes larger at higher redshift (Nilsson et al. 2009; Hayes et al. 2010). It is certainly interesting and important to test whether or not our model can reproduce not only the physical properties of observed LAEs but also their evolution. We will present the properties of simulated LAEs at various redshifts in a forthcoming paper (Shimizu, Yoshida & Okamoto, in preparation). We will also study the epoch of hydrogen reionization using our theoretical model.

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