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Lyman-α Emitters in Cosmological Simulations I: Lyman-α 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-α 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-α photons on the assumption that the clumpiness of the inter-stellar medium in a galaxy is correlated with the larger scale substructure richness. The radiative transfer effect proposed by Neufeld. (1991) allows a large fraction of Lyman-α 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, ultra-violet and Lyman-α luminosity functions, and the equivalent width distribution. A simple model that takes only dust absorption into account fails in matching the observational data, suggesting that the kind of effect we consider is needed. Our model also predicts a bimodal age distribution for LAEs. There are old, massive and dusty LAEs, similar to recently found high redshift LAEs. The large LAEs have escape fractions of Lyman-α photons of $f_{\rm esc} \sim 0.05 - 0.1$.

Key words: Galaxies – Lyα emitters; Galaxies – Formation; Galaxies – correlation function

1 INTRODUCTION

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

It is generally thought that the strong Lyα emission physically originates from star-forming regions (HII regions) in a young starburst galaxy. Some LAEs have very large equivalent widths ($\mathrm{EW_{Ly\alpha}}$) exceeding 400Å, 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 Lyα 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. Lyα photons are easily absorbed by dust and thus it is naively expected that 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 et al. 2007), more recent multi-wavelength observations of LAEs in optical, infrared and sub-millimeter suggest that there are LAEs that are indeed old and dusty (Finkelstein et al. 2007; Lai et al. 2008; Matsuda et al. 2007; Uchimoto et al. 2008; Finkelstein et al. 2009c; Tamura et al. 2009; Ono et al. 2010). Interestingly, such a population increases with decreasing redshift (Nilsson et al. 2009). There is even an evidence that some sub-millimeter galaxies show strong Lyα

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emission (Smail et al. 2004). The existence of a substantial amount of dust appears incompatible with strong Lyα emission. There must be a physical mechanism for Lyα 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 et al. (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 outskirt of a galaxy so that Lyα photons can escape easier than those emitted from the central region. Dayal et al. (2009, 2010, 2011) perform cosmological simulations, which reproduce well the UV and Lyα luminosity functions. Dayal et al. (2011) also calculate the neutral hydrogen fraction at $z = 5.7$ by using a combination of their LAE formation model and radiation transfer calculation of hydrogen reionization. In the most recent work of Dayal et al. (2011), absorption of Lyα photons by dust is treated in a very simple manner, where a dusty gas is a pure absorber.

It has been suggested that large-scale gas motions in and around galaxies can affect the absorption of Lyα photons (Zheng et al. 2010a,b). Strong galactic winds from Lyα emitting galaxies are indeed found in the local universe (Lequeux et al. 1995; Kunth et al. 1998, 2003; Mas-Hesse et al. 2003; Keel et al. 2005). Strong winds are also seen in high-z Lyman break galaxies (LBGs) with strong Lyα emission (Pettini et al. 2002; Shapley et al. 2006; Bower et al. 2004; Wilman et al. 2005; Frye et al. 2007; Pentericci et al. 2007; Tapken et al. 2007). Although the large-scale velocity structure is rather important, 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). It appears that another physical process is necessary for massive dusty galaxies to be bright LAEs.

Neufeld. (1991) proposed an important effect for Lyα transfer. In a clumpy, multi-phase inter-stellar medium (ISM), dust is locked up in small cold clouds. Lyα photons can then escape from the clumpy ISM *easier* than continuum photons because Lyα 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 Lyα emission from dusty galaxies but also the observed high equivalent widths (Hansen, & Oh. 2006; Kobayashi, Totani, & Nagashima. 2007, 2010; Finkelstein et al. 2008, 2009a,b). Clearly it is important to incorporate the effect 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 ΛCDM 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. Unlike in semi-analytic methods, we can directly study the internal structure of simulated galaxies as well as their spatial distribution in a cosmological volume.

Throughout this paper, we adopt the ΛCDM cosmology with the matter density $\Omega_{\rm M} = 0.27$, the cosmological constant $\Omega_\Lambda = 0.73$, the Hubble constant $h = 0.7$ in units of $H_0 = 100$ km s^{-1} Mpc^{-1}, the baryon density $\Omega_{\rm B} = 0.046$, 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 Lyα EW$_{\rm Ly\alpha}$ 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} Mpc on a side. The mass of a dark matter particle and that of a gas particle are $2.41 \times 10^8 h^{-1}{\rm M}_\odot$ and $4.95 \times 10^7 h^{-1}{\rm M}_\odot$, respectively.

Physical processes such as star formation and feedback are implemented as in Okamoto, Nemmen & Bower. (2008); Okamoto, & Frenk. (2009); 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, σ, is strongly correlated with the maximum circular velocity of host (sub-) halos, $v_{\rm max}$, 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) is highest at early times (or in small halos). 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; Okamoto, Nemmen & Bower. 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 description. Each SPH particle can spawn a new star particle when the particle satisfies a set of standard criteria for star formation. A star particle carries its properties such as mass, formation time and metallicity. We calculate the spectral energy distribution (SED) of each star particle using the population synthesis code PÉGASE (Fioc & Rocca-Volmerange. 1997). We then sum the individual SEDs to obtain the total SED of a simulated galaxy.

We run a friends-of-friends group finder (Davis et al. 1985) to locate groups of stars, i.e., galaxies. We also identify substructures (subhalos) 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. Finally, we calculate the effect of dust extinction on ultra-violet 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 to metal mass ratio is a constant of 0.4, consistent with the local value. Note that the metallicity 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 $\tau_{\rm d}(\lambda)$ for UV continuum photons as

$$\tau_d(\lambda) = \frac{3\Sigma_d}{4a_{\rm d}s}, \tag{1}$$

where $a_{\rm d}$ and s are the typical size of dust grains, and the material density of dust grains, respectively. We adopt the standard choice of $a_{\rm d} = 0.1$ μm and $s = 2.5$ g cm^{-3} (Todini & Ferarra. 2001; Nozawa et al. 2003). The dust surface mass density Σ_d is

$$\Sigma_d = \frac{M_{\rm d}}{\pi r_{\rm d}^2}, \tag{2}$$

where $M_{\rm d}$ and $r_{\rm d}$ are the total dust mass (40% of metal mass) and the effective radius of the galaxy, respectively. The effective radius $r_{\rm d}$ is a fraction of the virial radius and is given by $f_{\rm d} r_{\rm vir}$ with $f_{\rm d} = 0.18$. The escape fraction of UV continuum photons $f_{\rm cont}(\lambda)$ is then calculated as

$$f_{\rm cont}(\lambda) = \frac{1 - \exp\left(-\tau_{\rm d}(\lambda)\right)}{\tau_{\rm d}(\lambda)}. \tag{3}$$

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 1216Å following Madau. (1995).

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

$$\tau^{\rm abs}_{\rm Ly\alpha} = c_{\rm abs}\tau_{\rm d}, \tag{4}$$

where $c_{\rm abs}$ is a constant parameter. Then, the escape fraction of Lyα photons $f^{\rm abs}_{\rm Ly\alpha}$ is given by

$$f^{\rm abs}_{\rm Ly\alpha} = \frac{1 - \exp\left(-\tau^{\rm abs}_{\rm Ly\alpha}\right)}{\tau^{\rm abs}_{\rm Ly\alpha}}. \tag{5}$$

We call this model as pure absorption model. Essentially, dust is treated as a pure absorber of Lyα photons in this model (e.g., Dayal et al. (2009, 2010, 2011)). Lyα photons can not 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 inter-stellar medium (ISM) model of Neufeld. (1991). In a clumpy ISM, Lyα photons are scattered mostly at the surface of cold clumps before they are absorbed by dust. A large fraction of Lyα 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 a galaxy. In practice, we use the number of subhalos (satellites) $N_{\rm sub}$ of the galaxy as a measure of its "clumpiness". We introduce the clumpiness factor S, which depends on $N_{\rm sub}$, and express the effective optical depth of Lyα line as

$$\tau^{\rm sub}_{\rm Ly\alpha} = c_{\rm sub} S \tau_{\rm d}, \tag{6}$$

where $c_{\rm sub}$ is a normalization constant. For simplicity, we assume the clumpiness factor is expressed as a power-law

$$S = N^{\alpha}_{\rm sub}. \tag{7}$$

After some experiments, we find that setting $\alpha = -0.5$ 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 Lyα photons $f^{\rm sub}_{\rm Ly\alpha}$ in this model is given by

$$f^{\rm sub}_{\rm Ly\alpha} = \frac{1 - \exp\left(-\tau^{\rm sub}_{\rm Ly\alpha}\right)}{\tau^{\rm sub}_{\rm Ly\alpha}}. \tag{8}$$

The combination of equation (7) and equation (8) effectively yields a larger escape fraction for a dusty but "clumpy" galaxy. Finally, we fix the normalization constants in the two models, $c_{\rm abs}$ and $c_{\rm sub}$, by matching the number density of simulated LAEs with the observed number density $n_{\rm LAEs} \sim 5 \times 10^{-4}$ [Mpc^{-3}] (Ouchi et al. 2008). We identify simulated galaxies which satisfy ${\rm EW}_{\rm Ly\alpha} > 20$Å and $L^{\rm obs}_{\rm Ly\alpha} > 1.0 \times 10^{42}$[erg/s] as LAEs.

3 RESULT

3.1 The Spatial Distribution of Simulated LAEs

Fig. 1 shows the projected distribution of the LAEs at $z = 3.1$ in the simulation volume of 100 comoving h^{-1}Mpc on a side. The point size represents the Lyα luminosity of each galaxy. Luminous LAEs are shown by large and red 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, although the difference is small.

We quantify the spatial distribution of the simulated LAEs. We calculate the two-point angular correlation function (ACF) and compare it with the observed correlation function. The ACF of LAEs found in the SSA22 field (Hayashino et al. 2004) is used for the comparison. Fig. 2 shows the ACFs for the two models. Both of the models reproduce the observational result well. The LAEs are hosted by dark halos with mass of $\sim 10^{11}{\rm M}_\odot$.

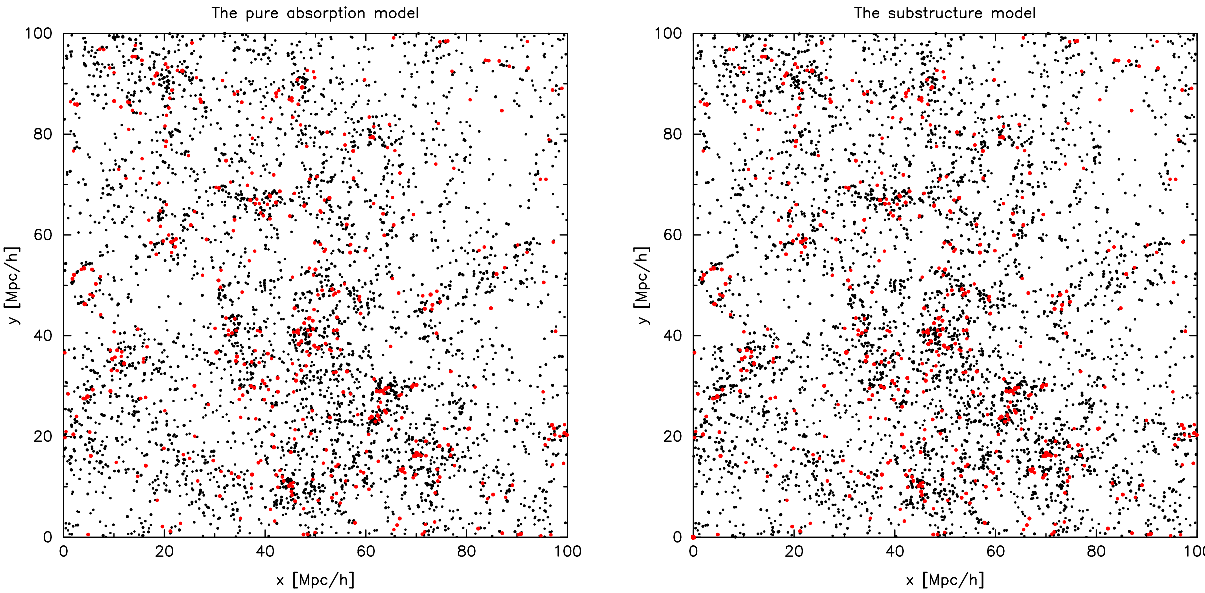

Figure 1. The spatial distribution of simulated LAEs. The left and right panels show LAEs in the pure absorption model and those in the substructure model, respectively. The point size is scaled with Lyα luminosity of each galaxy so that luminous galaxies appear as large points. The smallest and biggest points correspond to LAEs with $10^{42} \leqslant L_{\mathrm{Ly}\alpha} \leqslant 10^{42.2}\mathrm{erg s}^{-1}$ and $L_{\mathrm{Ly}\alpha} \geqslant 10^{43}\mathrm{erg s}^{-1}$, respectively. The red-points shows brightest LAEs ($> 6 \times 10^{42}$ [erg/s]).

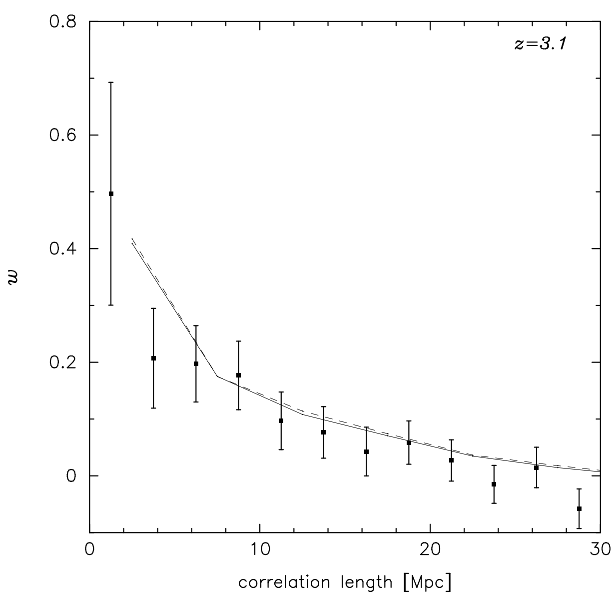

Figure 2. The two-point angular correlation function (ACF). The solid and dashed lines represent the substructure model and the pure absorption model, respectively. Points with error bar are the ACF of LAEs observed in SSA22a field (Hayashino et al. 2004).

3.2 Lyα Luminosity Functions

In Fig. 3, we compare the Lyα luminosity functions with the observational data at $z = 3.1$ (Ouchi et al. 2008). The pure absorption model (left panel) does not reproduce the observational data at the bright end. It predicts a smaller number of LAEs by a factor of ten at $L_{\mathrm{Ly}\alpha} \sim 10^{43}\mathrm{ergs}^{-1}$. In both our models, the intrinsic Lyα luminosity of a galaxy is proportional to its star formation rate (SFR), and thus the *intrinsically* bright LAEs are hosted typically by massive halos. However, such massive galaxies are also aged and dusty. Because of the strong dust absorption of Lyα photons (see equation [4]), dusty star-forming galaxies do not appear as LAEs in the pure absorption model.

Our substructure model, on the other hand, shows a substantially better agreement with the observational data. In the substructure model, dusty, aged and massive galaxies have complex internal structures. We assume that the evolved galaxies have also a more complex ISM structure, where Lyα photons can escape easily because of the Neufeld effect. Thus, even aged and dusty galaxies appear as bright LAEs and the resulting luminosity function matches the observation very well at the bright-end.

Interestingly, the substructure model predicts that the Lyα escape fraction of massive galaxies is $f_{\mathrm{esc}} \sim 0.05 - 0.1$, with a substantial dispersion. In the pure absorption model, the Lyα escape fraction decreases proportionally to the halo mass because of the size effect and also because massive galaxies are more metal-enriched.

3.3 $\mathrm{M_{UV}} - \mathrm{EW_{Ly\alpha}}$ distribution

Fig. 4 shows the distributions of our simulated LAEs in the $\mathrm{M_{UV}} - \mathrm{EW_{Ly\alpha}}$ plane at $z = 3.1$. In this plot, both models appear similar, with the LAEs populating the region where the observational data points also lie. Although both the models reproduce the observed trend that the equivalent width decreases with UV luminosity, only the substructure model predicts the existence of UV bright galaxies ($M_{\mathrm{UV}} < -20$) with large $\mathrm{EW_{Ly\alpha}} > 100$Å. This is again owing to the effect of enhanced Lyα luminosity in the substructure model. We also note here that the substantial dispersion of $\mathrm{EW_{Ly\alpha}}$ for UV bright LAEs, as is also found in the observations, is important. Apparently the Lymanα escape fraction is not

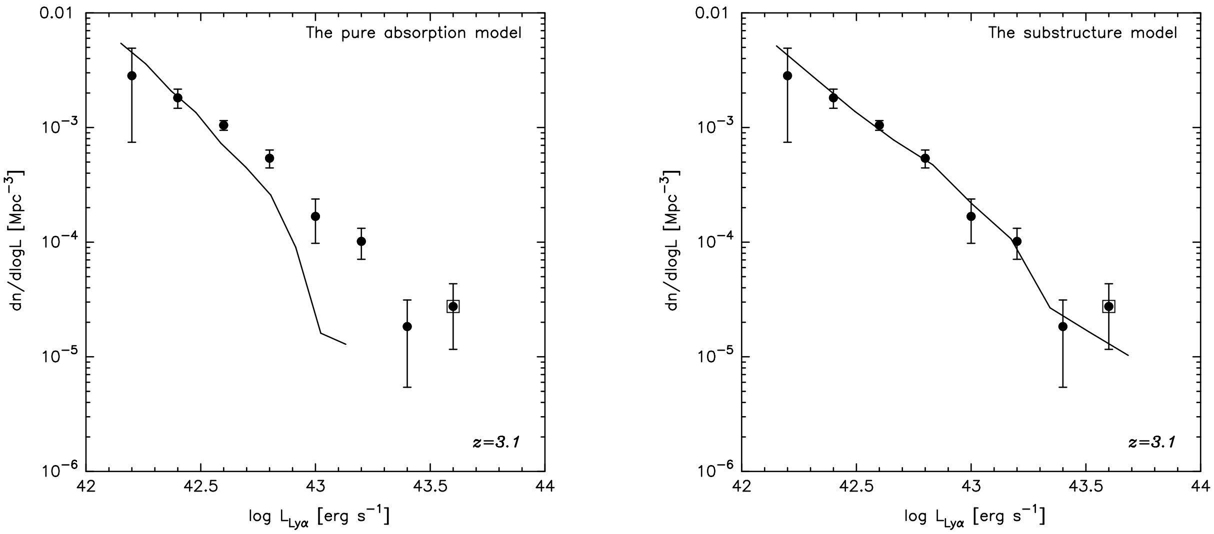

Figure 3. The Lyα luminosity function for the pure absorption model (left) and for the substructure model (right). We compare the model predictions with the observational data of Ouchi et al. (2008) with error bars. The filled circle marked an open square indicates LAE with AGN.

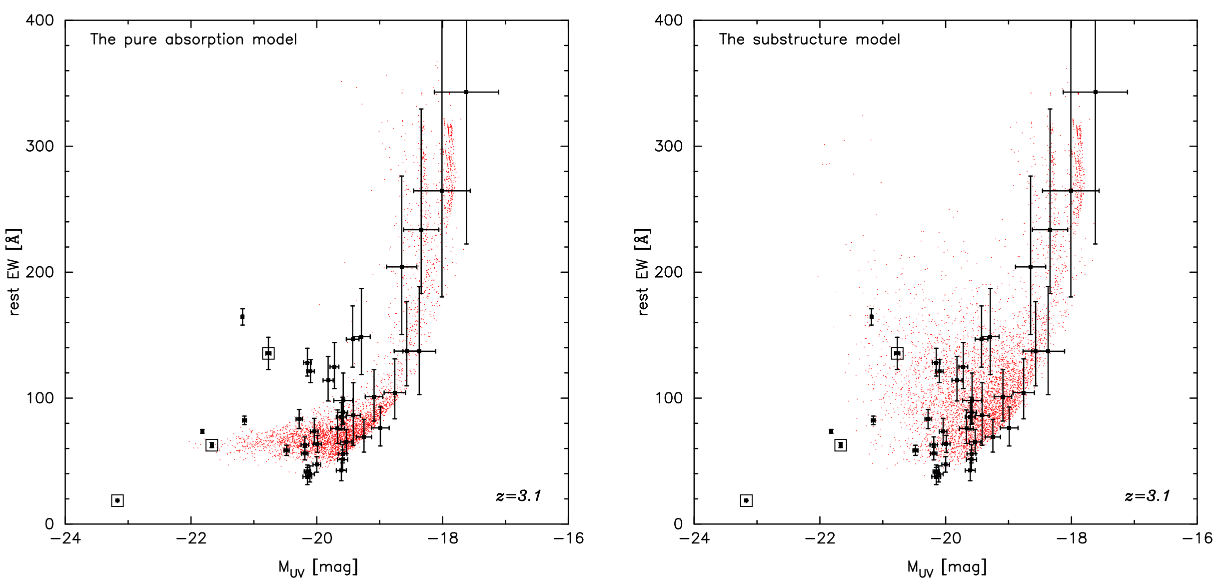

Figure 4. Distributions of LAEs in the $M_{UV} - EW_{Ly\alpha}$ plane at $z = 3.1$. The simulated LAEs are shown by dots, whereas points with error bars are observational data of Ouchi et al. (2008). The filled circles marked an open square indicate LAEs with AGN.

a simple function of the galaxy mass only. We discuss this issue more in detail in the discussion section.

3.4 Lyα Equivalent Width Distribution

In Fig. 5, we compare the rest-frame Lyα equivalent width of simulated LAEs (histograms) with the observational data (solid line with error bars). In the pure absorption model, $EW_{Ly\alpha}$ distribution is approximately-constant at $EW_{Ly\alpha} > 100$Å whereas the observed distribution decreases toward high $EW_{Ly\alpha}$. The substructure model reproduces the observed $EW_{Ly\alpha}$ distribution very well. It is interesting that the fraction of large $EW_{Ly\alpha}$ galaxies is similar between the two models. However, the substructure model predicts more LAEs with $EW_{Ly\alpha} \sim 100 - 200$Å. For these LAEs, UV continuum is absorbed by dust significantly but Lyα photons can escape again by the scattering effect.

3.5 Age distribution of simulated LAEs

Finally, we show the age distribution of simulated LAEs in Fig. 6. We assign the age of a simulated LAE by calculating the mass weighted mean of the stellar ages. The simulated LAEs shows clearly a bimodal distribution. Recently formed galaxies are young LAEs, whereas massive, dusty galaxies with $t_{\rm age} > 10^8$ years can also appear as bright LAEs. The latter population is indeed found recently by Finkelstein et al. (2009b).

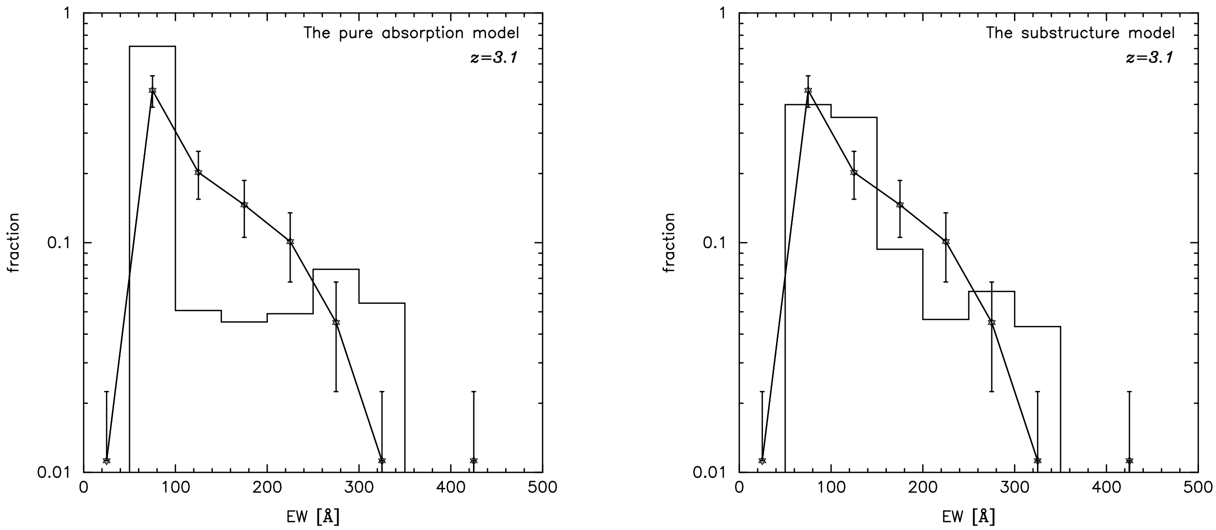

Figure 5. The rest-frame Lyα equivalent width ($\mathrm{EW_{Ly\alpha}}$) distribution at $z = 3.1$. The histogram shows our model results, whereas the solid lines with error bars show observational results (Ouchi et al. 2008).

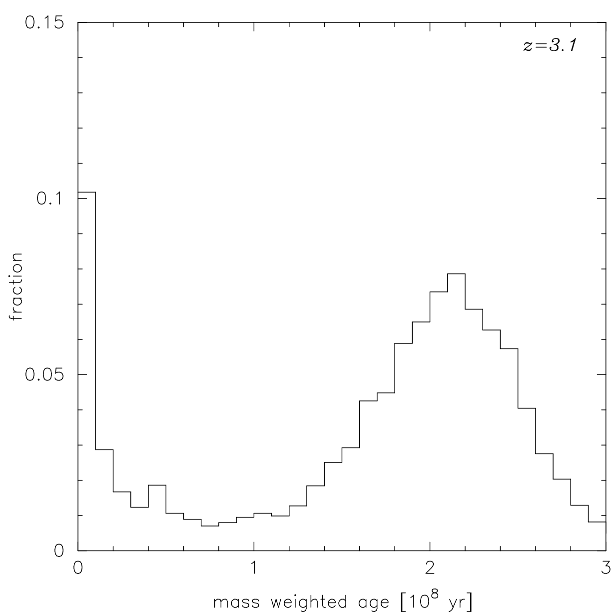

Figure 6. The age distribution of simulated LAEs for the substructure model. There are two types LAEs; young LAEs that are populated at the left of the plot and old LAEs that are broadly distributed around $t_{\rm age} \sim 2 \times 10^8$ years.

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, Nemmen & Bower. (2008). We develop a novel model in which Lyα photons can escape from a massive, dusty galaxy if the ISM is clumpy. The idea is motivated by the multiple scattering and escape of Lyα photons originally proposed by Neufeld. (1991).

Our physical model of LAEs reproduces not only the Lyα luminosity function but also $\mathrm{M_{UV}} - \mathrm{EW_{Ly\alpha}}$ distribution, 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 observational results using cosmological hydrodynamic simulations. Interestingly, the model predicts the Lyα escape fraction is roughly constant for the massive LAEs. Massive, dusty and aged galaxies can appear as bright LAEs, as is consistent with recent observations. Contrastingly, the pure absorption model fails in reproducing many of the observational results. We argue that the kind of effect to enhance Lyα photon escape from massive dusty galaxies is necessary for modeling LAEs.

It is interesting to ask if the Lyα escape fraction can be described as a simpler function of galaxy mass. In our simulation, the substructure abundance of simulated galaxies roughly scales with their host halo mass, although with substantial dispersions. It has turned out that the dispersion is also important to reproduce some observational results. To explicitly test the idea, we have employed a simpler model in which the Lyα 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 found that this simple model fails in reproducing the $\mathrm{M_{UV}} - \mathrm{EW_{Ly\alpha}}$ distribution and ACF. The simple model boosts the Lyα luminosity too much and cannot explain the existence of UV-bright LAEs with low equivalent widths (see Fig. 4). 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 upper bound of the current data. Overall, we conclude that the internal structure of a galaxy is an important factor to determine its appearance as a LAE. Interestingly, Charlot, & Fall. (1993) argue that a large scatter of Lyα emission versus metallicity correlation might be caused by the structure of the interstellar medium.

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 are available. According to very recent observations, the fraction of old population in observed LAEs increases with decreasing redshift, whereas the escape fraction of Lyα 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 et al. 2011 in prep). We will also study the epoch of hydrogen reionization using our theoretical model.

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