A PHYSICAL MODEL OF Lyα EMITTERS

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ABSTRACT

We present a simple physical model for populating dark matter halos with Lyα emitters (LAEs) and predict the properties of LAEs at $z \approx 3–7$. The central tenet of this model is that the Lyα luminosity is proportional to the star formation rate (SFR) which is directly related to the halo mass accretion rate. The only free parameter in our model is the star formation efficiency (SFE). An efficiency of 2.5% provides the best fit to the Lyα luminosity function (LF) at redshift $z = 3.1$, and we use this SFE to construct Lyα LF s at other redshifts. Our model reproduces the Lyα LFs, stellar ages, SFRs $\approx 1–10 M_\odot$ yr$^{-1}$, stellar masses $\approx 10^8$ to $10^9 M_\odot$, and the clustering properties of LAEs at $z \approx 3–7$. We find the spatial correlation lengths $r_s \approx 3–6 h^{-1}$ Mpc, in agreement with the observations. Finally, we estimate the field-to-field variation $\approx 30\%$ for current volume and flux limited surveys, again consistent with observations. Our results suggest that the star formation, and hence Lyα emission in LAEs can be powered by accretion of new material. Relating the accreted mass, rather than the total mass, to the Lyα luminosity of LAEs naturally gives rise to their duty cycle.

Key words: accretion, accretion disks – dark matter – galaxies: evolution – galaxies: halos – galaxies: high-redshift – galaxies: luminosity function, mass function

Online-only material: color figures

1. INTRODUCTION

Lyα emitting galaxies (LAEs) are selected on the basis of strong Lyα emission line, irrespective of other galaxy properties (e.g., Cowie & Hu 1998; Rhoads et al. 2000, 2004; Rhoads & Malhotra 2001; Fynbo et al. 2001; Ajiki et al. 2003; Matsuda et al. 2005; Taniguchi et al. 2005; Wang et al. 2005; Gawiser et al. 2006; Shimasaku et al. 2006; Tapken et al. 2006; Murayama et al. 2007; Nilsson et al. 2007; Ouchi et al. 2008). However, high-redshift galaxies selected on the basis of one of these properties are reasonably uniform in some of their other properties. For example, the inferred stellar mass of LAEs at $z < 5$ is typically small, $\sim 10^7$ to $10^9 M_\odot$ (Gawiser et al. 2006; Pirzkal et al. 2007; Finkelstein et al. 2007; Pentericci et al. 2009) and they often have large Lyα equivalent width (EW) indicating a young stellar population (Malhotra & Rhoads 2002), which is also supported by the blue color of these galaxies (Venemans et al. 2005; Gawiser et al. 2006; Pirzkal et al. 2007; Finkelstein et al. 2007, 2008), especially at high redshifts. Active galactic nuclei (AGNs) are ruled out as sources of strong Lyα emission in LAEs due to non-detection of X-ray emission (Malhotra et al. 2003; Wang et al. 2004; Gawiser et al. 2007) and the lack of high ionization line in the optical spectra (Dawson et al. 2004, 2007; Wang et al. 2009). LAEs have moderate SFRs $\approx 5–8 M_\odot$ yr$^{-1}$ (e.g., Pirzkal et al. 2007; Taniguchi et al. 2005) and spatial correlation lengths of $\approx 3–5 h^{-1}$ Mpc, albeit with a substantial uncertainty (Ouchi et al. 2003; Kovač et al. 2007; Gawiser et al. 2007).

Despite the increasing number of LAE observations, theoretical understanding of LAEs is still in early stages, primarily due to a poor understanding of physical properties including star formation, stellar initial mass function, Lyα escape fraction, and the duty cycle of the Lyα phase. There have been several theoretical studies of LAEs based on cosmological simulations (e.g., Barton et al. 2004; Davé et al. 2006; Tasitsimi 2006; Shimizu et al. 2007; Nagamine et al. 2008), semi-analytical models (e.g., Le Delliou et al. 2006; Kobayashi et al. 2007, 2009; Dayal et al. 2008; Samui et al. 2009) and analytical models (e.g., Haiman & Spaans 1999; Dijkstra et al. 2007; Mo et al. 2007; Stark et al. 2007; Fernandez & Komatsu 2008) that relate the total halo mass to the Lyα luminosity of LAEs. Such a linear relationship between the halo mass and Lyα luminosity often leads to an overprediction of the number density of LAEs. To reconcile the mass distribution of halos to the luminosity function (LF), one needs to either assume a small escape fraction of Lyα photons (which fails to account for the large Lyα EWs observed) or introduce a duty cycle (e.g., Stark et al. 2007; Nagamine et al. 2008) which adds another parameter to the models. In addition, the complexity and large number of variable parameters in many models motivate the development of a simple approach, which is particularly useful in understanding the nature of LAEs observed at high redshifts.

In this paper, we present a physical model to populate dark matter (DM) halos with LAEs in a cosmological simulation, and predict the abundances and physical properties at $z \approx 3–7$. This model differs fundamentally from many of the earlier studies in that we relate mass accreted, as opposed to the total halo mass, to the Lyα luminosity. Mass accretion onto halos via smooth infall and accretion due to mergers of a specific mass ratios has been shown to have distinctly different clustering...
behavior (Scannapieco & Thacker 2003). However, in our current work we do not distinguish between smooth accretion and the accretion due to mergers. In other words, in our model the LAEs are undergoing an episode of star formation driven by accretion of fresh material onto the halos, independent of whether the accretion is due to mergers or via smooth infall. While there is no direct observational evidence showing a relation between the baryons accreted and the Lyα luminosity, recent studies (e.g., Dekel et al. 2009; Kereš et al. 2009) have detailed description of our physical model. We describe the DM parameter in our model.

While there is no direct observational evidence showing a relation between accretion rates and Lyα emission, construct UV LF of our model LAEs and compare the mass in our model LAEs to compare with the dust estimates from No. 1, 2009 PHYSICAL MODEL OF Lyα EMITTERS. We populate each DM halo with an LAE, and assign to it Lyα luminosity \( L_{\text{Ly}\alpha} \) proportional to the SFR using the following equation:

\[
L_{\text{Ly}\alpha} = 1 \times 10^{42} \times \frac{\text{SFR}}{M_\odot \text{yr}^{-1}} \text{ erg s}^{-1}.
\]  

Here \( L_{\text{Ly}\alpha} \) is the intrinsic luminosity of an LAE. The observed Lyα flux will also depend on the escape fraction of the Lyα photons \( f_{\text{esc}} \). Moreover, Equation (1) implicitly assumes an escape fraction near zero for the ionizing continuum photons, whose absorption is required to produce the Lyα emission line.

While the escape fraction of ionizing Lyman continuum photons (\( \lambda < 912 \, \text{Å} \)) is not very precisely known, several studies have shown that an escape fraction of only a few percent is sufficient to meet the observational constraints on the reionization epoch (e.g., Wood & Loeb 2000; Hansen & Oh 2006; Razoumov & Sommer-Larsen 2006; Gnedin et al. 2008). In addition, observations are also generally consistent with small escape fractions of Lyman continuum photons both locally (Leitherer et al. 1995) and at high redshifts (e.g., Hansen & Oh 2006; Shapley et al. 2006).

The escape fraction of Lyα photons \( f_{\text{esc}} \) is likely to be large with \( f_{\text{esc}} \approx 1 \) causing the large observed Lyα EWs (Malhotra & Rhoads 2002; Finkelstein et al. 2007; Wang et al. 2009). However, the semi-analytic model of Le Delliou et al. (2006) predicts a much smaller value of \( f_{\text{esc}} \approx 2\% \) which is compensated by top-heavy initial mass function in their model. For simplicity, in our model we approximate \( f_{\text{esc}} \) and Lyman continuum photons as unity and zero, respectively. Thus, all the Lyα photons produced in LAEs escape to be observed while none of the ionizing photons escape from the galaxy. Small deviations from these assumptions will not affect our results significantly.

As stated earlier, in our model we assume that the accretion of new material on to DM halos causes star formation in LAEs. We estimate the SFR, i.e., the mass in accreted gas \( \Delta M_{\text{gas}} \) converted to stars in unit time, in LAEs by converting baryonic mass accreted \( \Delta M_b \) by DM halos, adopting a constant ratio of baryons to the DM, over a short timescale, \( \tau_{\text{Ly}\alpha} \). This timescale (\( \approx 30 \) Myr) is broadly similar to the stellar population ages of most Lyα galaxies (e.g., Pirzkal et al. 2007; Finkelstein et al. 2007, 2008), the lifetimes of OB associations, and the dynamical time expected for Lyα galaxies based on their measured sizes (Pirzkal et al. 2007). In addition, the dust produced in supernovae (SNe), which occurs approximately on timescales of \( \approx 30 \) Myr, may reduce the fraction of Lyα photons escaping from LAEs, thus giving rise to the duty cycle of LAEs (Kovač et al. 2007), which is also reproduced in our model. A similar timescale (\( \approx 70 \) Myr) was used by Shimizu et al. (2007) to match the morphology of large-scale structure of LAEs by varying the amplitude of density fluctuations in galaxy formation models.

Thus,

\[
\text{SFR} = f_s \times \left( \frac{\Delta M_{\text{gas}}}{L_{\text{Ly}\alpha}} \right) = f_s \times \left( \frac{\Delta M_b}{L_{\text{Ly}\alpha}} \right) = f_s \times \dot{M}_b, \tag{2}
\]

where \( f_s \) is the SFE. In the above equation, we have assumed that \( \Delta M_{\text{gas}} \) is same as the baryonic mass accreted \( \Delta M_b \) by the DM halos, and since our simulation contained only DM particles, we use the universal ratio of baryonic and DM densities, i.e., \( \Delta M_b = (\Omega_b/\Omega_{\text{DM}}) \times \Delta M_{\text{DM}} \), where \( \Omega_b \) and \( \Omega_{\text{DM}} \) are the.

Our model is motivated by the idea that Lyα emission in LAEs is associated with star formation (Partridge & Peebles 1967) from rapid accretion of new material onto the DM halos. This new material provides fresh fuel to the system driving the star formation (Kereš et al. 2009).
baryonic and DM density parameters and $\Delta M_{DM}$ is the DM mass accreted by the DM halos.

Finally, the total mass in young stars in a LAE, is estimated using

$$ M_* \approx SFR \times t_{Ly\alpha} = f_* \times M_h \times t_{Ly\alpha} = f_* \times \frac{\Omega_b}{\Omega_{DM}} \times \Delta M_{DM}. \quad (3) $$

This corresponds to the mass of stars younger than 30 Myr which contribute to the Ly$\alpha$ and UV continuum emission, which is more easily measured than the total stellar mass. The only unknown variable in all of the above equations is $f_*$, the only free parameter in our model. Here we note that $f_*$ and $\Omega_b/\Omega_{DM}$ ratio in the above equations are degenerate and these values may vary somewhat for individual galaxies.

3. SIMULATION AND HALO CATALOGS

We constructed the DM halo catalog using an $N$-body DM cosmological simulation code GADGET2 (Springel 2005). We generated the initial conditions for the simulation using second-order Lagrangian perturbation theory (Crocce et al. 2006; Thacker & Couchman 2006). In this simulation, we use $10^{24}$ DM particles in a comoving volume of $(102 \, \text{Mpc})^3$, a volume greater than a typical LAE survey. Each DM particle has a mass $\approx 2.7 \times 10^7 M_\odot \, h^{-1}$. Using a friends-of-friends (FOF) halo finder (Davis et al. 1985), we identify DM halos that contain 100 or more DM particles. This corresponds to a minimum halo mass $\approx 2.7 \times 10^9 M_\odot h^{-1}$. We then generate catalogs for redshifts from $z = 10$ to $z = 3$, which contain positions of halos, their DM mass, and unique IDs of each individual particle that belongs to a given halo. These unique particle IDs are later used to track halos between two epochs. Throughout this work, we assumed a flat ΛCDM cosmology with parameters $\Omega_{\Lambda} = 0.233$, $\Omega_m = 0.721$, $\Omega_b = 0.0462$, $h = 0.71$, and $\sigma_8 = 0.817$, where $\Omega_m$, $\Omega_\Lambda$, $\Omega_b$, $h$, and $\sigma_8$ correspond, respectively, to the matter density, dark energy density, and baryonic density in units of the critical density, the Hubble parameter in units of 100 km s$^{-1}$ Mpc$^{-1}$, and the rms density fluctuations on the 8 Mpc $h^{-1}$ scale, in agreement with WMAP (Spergel et al. 2007) five-year results (Hinshaw et al. 2009).

4. Lyα LUMINOSITY FUNCTION

We now construct the Lyα LF, the number of LAEs per unit volume in a given luminosity bin. First, we calculate the total DM mass accreted ($\Delta M_{DM}$) by each DM halo at $z = 3.1$ during an interval $\approx 30$ Myr (equals $t_{Ly\alpha}$ in Equation (2)). To calculate $\Delta M_{DM}$ we track each halo, using the unique ID associated with particles in a given halo, between two epochs separated in time $t_{Ly\alpha}$. In general, we expect every halo to accrete more mass with time. However, due to group finding noise, we find that some halos lose mass (negative mass accretion) between outputs. In other words, the mass accretion by some halos is not real but results from the simulation noise. The main reason for this noise is the way halos are identified in any DM simulation.

In our DM simulation, we use a FOF halo finder which links all the particles within a linking length from each other into a halo, independent of whether a given particle is gravitationally bound to a halo. Thus, associating a particle with a halo based on the linking length gives rise to some uncertainty in halo mass (in this case $\Delta M_{DM}$). To determine how many halos have real accretion, rather than spurious apparent accretion due to uncertainty in particle association with a halo by the halo finder, we first construct a histogram of $\Delta M_{DM}$ including the halos with negative $\Delta M_{DM}$. We then subtract the halo counts in negative $\Delta M_{DM}$ bins from the corresponding counts in the positive $\Delta M_{DM}$ bins. This procedure compensates for halos that show accretion just due to random nature of a FOF halo finder. The remaining halos with positive accretion rates are then considered for constructing Lyα LFs.

Next, we convert the accreted mass bins to the Lyα luminosity bins using Equation (1) to yield Lyα LF. We then compare this LF with the observations at $z = 3.1$ (Gronwall et al. 2007), and get the best-fit model by varying the SFE ($f_*$) to yield the least reduced $\chi^2$ (per degree of freedom) given by

$$ \chi^2 = \frac{1}{N - 1} \sum \frac{(N_{\text{model}} - N_{\text{obs}})^2}{\sigma_{\text{model}}^2 + \sigma_{\text{obs}}^2}, $$

where $N$, $N_{\text{model}}$, and $N_{\text{obs}}$ are the number of observed data points, LAE counts from model, and the observed LAE counts in each bin, respectively, and the Poisson errors are given by $\sigma_{\text{model}} = \sqrt{N_{\text{model}}}$ and $\sigma_{\text{obs}} = \sqrt{N_{\text{obs}}}$. Figure 1 (top left) shows the best-fit model Lyα LF (dotted line) at $z = 3.1$. The symbols are the observations from Gronwall et al. (2007) shown with 1σ error bars.

Lastly, we use the best-fit model parameter $f_*$, i.e., the SFE at $z = 3.1$ to construct the model Lyα LFs at $z > 3$, and then compare these LFs with the observations at $z = 4.5, 5.7$, and 6.6. Figure 1 shows the Lyα LFs from our model (dotted lines) and observations (filled circles) at redshifts $z = 3.1$ (Gronwall et al. 2007), $z = 4.5$ (Dawson et al. 2007), $z = 5.7$ (Ouchi et al. 2008), and $z = 6.6$ (Kashikawa et al. 2006). We have rebinned the observational data for $z = 3.1$ and $z = 6.6$ data so as to make the bin size uniform at all redshifts. Wigglies seen, especially in the $z = 4.5$ model Lyα LF (Figure 1, top right) are probably due to statistical noise. The best-fit model for $z = 3.1$ Lyα LF yields a SFE of 2.5%. Corresponding to this SFE, the $\chi^2$ values
between our model and the observed Ly\(\alpha\) LFs are 0.5, 0.8, 1.2 and 1.5 for Ly\(\alpha\) LFs at \(z = 3.1, 4.5, 5.7,\) and 6.6, respectively.

5. RESULTS

Our model Ly\(\alpha\) LFs with single SFE, agree remarkably well with the observations (Dawson et al. 2007; Ouchi et al. 2008). They reproduce, without any additional parameters, the duty cycle of \(~10\%\) obtained from clustering studies (Kovač et al. 2007). To predict the Ly\(\alpha\) LFs of LAEs, Nagamine et al. (2008) investigated two models, the duty cycle and escape fraction scenario, and found that the duty cycle model reproduces observations better than the escape fraction model. In our model, the duty cycle is naturally produced since only halos with high accretion rates will be observed as LAEs. Figure 2 shows the halo mass function at \(z = 3.1\) (violet), \(z = 4.5\) (blue), \(z = 5.7\) (green), and \(z = 6.6\) (red). The dashed blue line shows the DM halo mass functions at \(z = 4.5\) to compare with the corresponding accreted mass function. The vertical dotted lines enclose the region of observed Ly\(\alpha\) luminosities in LAEs.

(A color version of this figure is available in the online journal.)

Figure 2. Accreted mass function and halo mass functions. Solid lines show accreted mass functions at \(z = 3.1\) (violet), \(z = 4.5\) (blue), \(z = 5.7\) (green), and \(z = 6.6\) (red). The dashed blue line shows the DM halo mass functions at \(z = 4.5\) to compare with the corresponding accreted mass function. The vertical dotted lines enclose the region of observed Ly\(\alpha\) luminosities in LAEs.

5.1. Physical Properties of LAEs

We use the best-fit model parameter (SFE) at \(z = 3.1\) to derive other physical properties of LAEs and compare our results with the observations. Our best-fit model yields an SFE of 2.5\%, consistent with the global SFE. Fukugita et al. (1998) predicted a SFE \(< 5\%\), while Baldry et al. (2008) found this value in the range 4\%–8\% for blue light in galaxies. While our model predicts a roughly constant SFE over a wide redshift range, in reality this value will vary somewhat depending on the ratio of baryons to DM.

The SFE of 2.5\% yields SFRs \(\approx 1–10 M_\odot \text{yr}^{-1}\) corresponding to the observed Ly\(\alpha\) luminosity range \(L_{\text{Ly}\alpha} \approx (1 \times 10^{42})–(1 \times 10^{43}) \text{ erg s}^{-1}\). This SFR is comparable to the inferred SFR \(\approx 8 M_\odot \text{yr}^{-1}\) in LAEs at \(z \approx 5\) (Pirzkal et al. 2007). A similar average value of SFR \(\approx 6 M_\odot \text{yr}^{-1}\) was inferred for \(z = 3.1\) LAEs (Gawiser et al. 2006). A slightly higher value of SFR \(\approx 5.7–28.3 M_\odot \text{yr}^{-1}\) with median SFR \(\approx 9.6 M_\odot \text{yr}^{-1}\) was inferred for \(z = 5.7\) LAEs (Murayama et al. 2007). For \(z = 6.6\) LAEs, Taniguchi et al. (2005) found an average
SFR $\approx 5.7 \pm 2.3 \, M_\odot \, \text{yr}^{-1}$. These averages however depend on the depth of the surveys; deeper surveys probe less luminous galaxies and hence lower SFRs.

The total stellar mass in young stars (estimated using Equation (3)) of LAEs corresponding to the observed Ly$\alpha$ luminosity range is $M_\star \approx (3 \times 10^7) - (3 \times 10^8) \, M_\odot$, in good agreement with the observed stellar masses $\approx 10^7 \, M_\odot$ to $10^9 \, M_\odot$ of LAEs (Finkelstein et al. 2007; Gawiser et al. 2007; Pirzkal et al. 2007; Pentericci et al. 2009). Thus, our model reproduces the primary physical properties of LAEs at $z \approx 3-7$. In addition, our assumption of large escape fraction of Ly$\alpha$ photons will yield high observed EWs of Ly$\alpha$ line in LAEs (Malhotra & Rhoads 2002; Kudritzki et al. 2000; Dawson et al. 2004, 2007; Shimasaku et al. 2006; Wang et al. 2009).

5.3. UV Luminosity Function of LAEs

Our model, with single parameter, i.e., the SFE, reproduced the observed Ly$\alpha$ LFs over a wide range of redshifts, $z = 3–7$. Now we compare the UV LFs of our model LAEs with the observations at $z = 3.1$ (Gronwall et al. 2007; Ouchi et al. 2008) and $z = 5.7$ (Ouchi et al. 2008). We convert Ly$\alpha$ luminosity to UV luminosity using the following relation (Madau et al. 1998):

$$L_{UV} (\text{erg s}^{-1} \text{Hz}^{-1}) = 8 \times 10^{27} \times \text{SFR}(M_\odot \, \text{yr}^{-1}),$$

where $L_{UV}$ is the UV luminosity at 1500 Å, and SFR is the star formation rate of our model LAEs calculated using Equation (2). Figure 4 shows the comparison between model predicted and observed UV LFs at $z = 3.1$ and $z = 5.7$. Filled and open circles are the observations from Ouchi et al. (2008) and Gronwall et al. (2007), respectively, while the dotted line is our model predicted UV LF. At $z = 5.7$, the model predicted UV LF agrees quite well with the observations, while at $z = 3.1$, the observed UV LFs of Ouchi et al. (2008) and Gronwall et al. (2007) brackets our model predicted UV LF.

5.4. Evolution of Ly$\alpha$ Luminosity Function

The Ly$\alpha$ LFs have been used to probe the epoch of reionization and constrain the evolution of intergalactic medium (IGM; e.g., Haiman & Spaans 1999; Malhotra & Rhoads 2004; Haiman & Cen 2005; Stern et al. 2005; Kashikawa et al. 2006; Dijkstra et al. 2007; McQuinn et al. 2007; Mesinger & Furlanetto 2007).
that the number density of LAEs, at $z$ also affects the Ly$\alpha$ addition, the cosmic variance in a volume limited LAE survey be attributed to the evolution of DM halo mass function. In a survey area of $0.5$ square degree, $<25$ Mpc$^3$ comparable to typical narrowband LAE surveys, the weak Ly$\alpha$ evolution at these redshifts. Dijkstra et al. (2007) showed that the weak Ly$\alpha$ evolution between $z = 5.7$ and $z = 6.6$ can be attributed to the evolution of DM halo mass function. In addition, the cosmic variance in a volume limited LAE survey also affects the Ly$\alpha$ LF. For example, Shioya et al. (2009) find that the number density of LAEs at $z \approx 5$ vary by a factor $\approx 2$ in a survey area of $0.5 \times 0.5$. We now investigate the evolution of Ly$\alpha$ LFs, and the effect of cosmic variance on number density of LAEs in a volume and flux limited LAE survey.

From Figure 2 we see that there is some evolution of number density of DM halos that can host LAEs. However, this weak evolution is due to the intrinsic change in the number density since we have not included any IGM correction in our model. Thus, our model can explain the observed evolution of Ly$\alpha$ LF (Kashikawa et al. 2006) without invoking sample variance or reionization. We now estimate the effect of sample variance on the Ly$\alpha$ LF.

In order to understand the effect of cosmic variance on the observed number density of LAEs in a volume and flux limited LAE survey, we estimate the field-to-field variance by dividing the total simulation volume into eight non-overlapping rectangular boxes, each with a comoving volume ($102 \times 51 \times 25$ Mpc$^3$) comparable to typical narrowband LAE surveys ($\approx 2 \times 10^5$ Mpc$^3$). The variance is calculated using $\sigma^2 = (N - \mu^2)/\mu$, where $N$ is the number of LAEs in each sub-volume and $\mu$ is the average number of LAEs. Figure 5 shows field-to-field variance, for a volume-limited LAE survey with different Ly$\alpha$ flux limit. For a narrowband LAE survey with Ly$\alpha$ detection limit of $L_{\text{Ly}\alpha} > 2 \times 10^{42}$ erg s$^{-1}$ and a survey volume $< 2 \times 10^5$ Mpc$^3$, the field-to-field variation is significant with $\sigma^2 > 30\%$. This result confirms the necessity of using a large volume to minimize sample variance in LAE surveys. It also strengthens our conclusion that some apparent evolution of Ly$\alpha$ LF can be attributed to the sample variance.

6. CLUSTERING OF LAEs

Previous studies (e.g., Iliev et al. 2008; Orsi et al. 2008) suggest that LAEs trace rarer and higher density regions. However, Shimizu et al. (2007) suggested that the LAEs at $z \approx 3$ do not necessarily reside in high density peaks. In this section, we investigate whether our model LAEs reside in high density regions and estimate their spatial correlation lengths. Figure 6 shows the spatial distribution of LAEs at two different redshifts, $z = 5.7$ and $z = 4.5$, in a simulation slice of $30 \times 30 \times 17 h^{-1}$ Mpc$^3$. The depth of this slice is comparable to the depth of a typical LAE survey. Comparing the locations of LAEs at two redshifts it is clear that different halos host LAEs at different redshifts, thus exhibiting a duty cycle (Kovač et al. 2007; Stark et al. 2007; Nagamine et al. 2008). Our model LAEs are generally located around overdense regions consistent with the observations and as expected in biased galaxy formation models.
6.1. Two-point Spatial Correlation Function

The two-point spatial correlation function $\xi(r)$ (Peebles 1980) is frequently used to study the clustering properties of galaxies (e.g., Zehavi et al. 2005; Gawiser et al. 2007; Kovač et al. 2007). We use the Landy–Szalay estimator, proposed by Landy & Szalay (1993), to calculate the two-point spatial correlation function given by

$$\xi(r) = \frac{DD(r) − 2DR(r) + RR(r)}{RR(r)},$$

(7)

where $DD(r)$, $RR(r)$, and $DR(r)$ are the number of galaxy–galaxy, random–random, and galaxy–random pairs, respectively, with separation distance of $(r, r + \delta r)$. To compare our model $\xi(r)$ with the observations and quantify its evolution with redshift we only include LAEs brighter than the detection limit of LAE surveys at a given redshift, and use our full simulation volume $\approx 1 \times 10^6$ Mpc$^3$ for better statistical significance.

To calculate $\xi(r)$ at each redshift, we generated a random sample of points with uniform coordinates drawn from a uniform probability distribution, and a number of random points exactly equal to the number of LAEs. We count the number of pairs, $DD(r)$, $RR(r)$, and $DR(r)$ separated by a distance $r$ by binning the points at different $r$ with binwidth of $\delta r = 0.2$ h$^{-1}$ Mpc. To minimize the random errors, we perform 50 realizations with different sets of random points and calculate an average $\xi(r)$ at each $r$. Using $r < 20$ h$^{-1}$ Mpc and assuming negligible error, we obtain the spatial correlation length $r_0$ by fitting a least-square power law to the correlation function.

The correlation lengths obtained from our model LAEs show a modest evolution, with $r_0 = (3.2 \pm 0.3, 5.0 \pm 0.3, 4.2 \pm 0.6, 6.0 \pm 1)$ h$^{-1}$ at $z = (3.1, 4.5, 5.7, 6.6)$, respectively. Figure 7 (left) shows a comparison between our model predictions (filled circles) and observed $r_0$ (shown with different symbols given in the labels) at different redshifts. The model predicted $r_0$ values are slightly shifted along the $x$-axis to avoid overlap with the observations. 

(A color version of this figure is available in the online journal.)
using contamination-corrected (the maximum value permitted) LAE sample. However, Ouchi et al. (2003) found a higher $r_0 = 6.2 \pm 0.5 \, h^{-1} \, \text{Mpc}$ for contamination-corrected LAE sample $z = 4.86$. We now estimate the variance of $r_0$ in a volume and flux-limited LAE survey, and see if we can account for the large difference seen in the observed $r_0$ between $z = 4.5$ and $z = 4.86$ LAE surveys.

To estimate the variance of $r_0$ ($\sigma^2_{r_0}$) in a volume and flux-limited LAE survey, we divide the total simulation volume at $z = 3.1$ into five non-overlapping sub-volumes, each with a comoving volume of $(102 \times 102 \times 20.4 \, \text{Mpc})^3$, approximately equal to a typical survey volume and only including LAEs with $L_{\text{Ly} \alpha} > 1 \times 10^{42} \, \text{erg s}^{-1}$. We calculate $\xi(r)$ and $r_0$, as described above (second paragraph) in each sub-volume and estimate $\sigma^2_{r_0}$ at $z = 3.1$. We find $\sigma^2_{r_0} = 0.5 \, h^{-1} \, \text{Mpc}$ with an average $r_0 = 3.2 \, h^{-1} \, \text{Mpc}$, average of $r_0$ in five sub-volumes. While this variance in $r_0$ cannot account for the large difference in $r_0$ observed between the two surveys at $z = 4.5$ and 4.86, it is clear that one needs to take into account such variance in correlation lengths obtained from volume and flux-limited surveys.

Finally, we investigate if the redshift evolution of $r_0$ seen in Figure 7 (left panel) is significant since this can result from the surveys at lower redshifts extending to lower luminosities and hence probing lower halo masses. In order to understand this effect, we consider full simulation volume and only include LAEs with a constant $L_{\text{Ly} \alpha} > 1 \times 10^{42} \, \text{erg s}^{-1}$ at all redshifts. Choosing a constant luminosity cutoff at all redshifts implies that we are probing approximately same halo masses at all redshifts. We calculate $r_0$ in the same way as described above (second paragraph) except that we impose the same luminosity cutoff at all redshifts. Figure 7 (right panel) shows $r_0$ with a constant lower luminosity at all redshifts. Most of this evolution seen in Figure 7 (left panel) can be attributed to the luminosity limit of different surveys probing different halo masses.

7. SUMMARY AND CONCLUSIONS

We have used a physical model with a single variable parameter to populate DM halos with LAEs in a cosmological simulation and compared our model predictions with the observations at redshifts $z \approx 3–7$. In our model, we assumed that the SFR, and hence the Ly$\alpha$ line luminosity is proportional to the mass accreted by halos. In other words, the star formation in LAEs mainly results from the accretion of new material. Despite the lack of observational evidence relating accretion rate to the Ly$\alpha$ luminosity of LAEs, it is promising that our model gives a good fit to the observations over a wide range of redshifts and is able to reproduce several other physical properties of LAEs. In addition, relating the accreted mass rather than the total halo mass to the Ly$\alpha$ luminosity gives rise to a duty cycle of LAEs quite naturally.

To compare our model predictions with observations, we first constructed the Ly$\alpha$ LF at $z = 3.1$ and obtained the best-fit model by varying the SFE and comparing the model Ly$\alpha$ LF with the observations at this redshift. We then used this best-fit model to predict the Ly$\alpha$ LFs and physical properties of LAEs at $z = 4.5, 5.7$ and $z = 6.6$.

Using a constant SFE, our model predicted Ly$\alpha$ LFs agree remarkably well with the LAE observations over a wide redshift range. Our best-fit model yields a SFE = 2.5% which gives SFR $\approx 1–10 \, M_\odot \, \text{yr}^{-1}$ in good agreement with the observations.

We find that the model LAEs in the currently observable luminosity range ($2 \times 10^{42} \, \text{erg s}^{-1} \lesssim L_{\text{Ly} \alpha} \lesssim 2 \times 10^{43} \, \text{erg s}^{-1}$) have stellar masses $\approx (3 \times 10^7) \text{ to } (3 \times 10^8) \, M_\odot$ of young (< 30 Myr) stars. These stellar masses of LAEs are similar to those inferred from observations (Finkelstein et al. 2007; Pirzkal et al. 2007). We have estimated the dust mass $M_{\text{dust}} \approx (4 \times 10^4) \text{ to } (2 \times 10^5) \, M_\odot$ for our model LAEs with $L_{\text{Ly} \alpha} = 1 \times 10^{43} \, \text{erg s}^{-1}$, in agreement with the inferred dust masses $\approx (3 \times 10^5) \text{ to } (4.5 \times 10^5) \, M_\odot$ from LAE observations at $z \approx 4.5$ (Finkelstein et al. 2008). Using our model LAEs, we constructed UV LF and compared it with the observations at $z = 3.1$ and $z = 5.7$. At $z = 5.7$, our model predicted UV LF of LAEs agrees quite well with the observations, while at $z = 3.1$, the observed UV LFs of Gronwall et al. (2007) and Ouchi et al. (2008) bracket our model-predicted UV LF.

While our model predicts a constant SFE, and hence a weak evolution of other physical properties of LAEs over a redshift range $z \approx 3–7$, this value also depends on the ratio of baryons to DM. Thus, in reality $f_*$ and hence other physical properties of LAEs might show detectable, albeit weak, evolution with redshift.

We also investigated the evolution of Ly$\alpha$ LFs from $z \approx 3–7$ and find that there is no significant evolution of Ly$\alpha$ LF due to the IGM if we include the intrinsic change in the number density of LAEs over this redshift range. This conclusion is strengthened if we include the effect of cosmic variance on the observed number density of LAEs. We show that the field-to-field variance can be large $\approx 30\%$ for a flux and volume-limited surveys comparable to current observations.

We studied the clustering properties of LAEs and found that the LAEs are mostly located in the high density peaks. Our model predicted correlation lengths $r_0 = (3.2 \pm 0.3, 5.0 \pm 0.3) \, h^{-1} \, \text{Mpc}$ which are in good agreement with the observations. We also estimate the variance ($\sigma^2_{r_0}$) in $r_0$ for a volume and flux-limited LAE survey and find that $\sigma^2_{r_0} = 0.5 \, h^{-1} \, \text{Mpc}$ at $z = 3.1$. Our models predict a modest evolution of the correlation length with redshift. Currently, there are no measurements of $r_0$ at $z > 5$ due to insufficient sample size of LAEs at higher redshifts. Therefore, more data are needed to test our predictions at higher redshifts in order to understand the evolution of $r_0$ with redshifts.

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