LYMAN ALPHA EMITTERS IN THE HIERARCHICALLY CLUSTERING GALAXY FORMATION

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ABSTRACT

We present a new theoretical model for the luminosity functions (LFs) of Lyα emitting galaxies in the framework of hierarchical galaxy formation. We extend a semi-analytic model of galaxy formation that reproduces a number of observations for local and high-z galaxies, without changing the original model parameters but introducing a physically-motivated modelling to describe the escape fraction of Lyα photons from host galaxies ($f_{\text{esc, Ly}\alpha}$). Though a previous study using a hierarchical clustering model simply assumed a constant and universal value of $f_{\text{esc, Ly}\alpha}$, we incorporate two new effects on $f_{\text{esc, Ly}\alpha}$: extinction by interstellar dust and galaxy-scale outflow induced as a star formation feedback. It is found that the new model nicely reproduces all the observed Lyα LFs of the Lyα emitters (LAEs) at different redshifts in $z \sim 3$–6. Especially, the rather surprisingly small evolution of the observed LAE Lyα LFs compared with the dark halo mass function is naturally reproduced. Our model predicts that galaxies with strong outflows and $f_{\text{esc, Ly}\alpha} \sim 1$ are dominant in the observed LFs. This is also consistent with available observations, while the simple universal $f_{\text{esc, Ly}\alpha} \sim 1$ model requires $f_{\text{esc, Ly}\alpha} \ll 1$ not to overproduce the brightest LAEs. On the other hand, we found that our model significantly overpredicts LAEs at $z \gtrsim 6$, and absorption of Lyα photons by neutral hydrogen in intergalactic medium (IGM) is a reasonable interpretation for the discrepancy. This indicates that the IGM neutral fraction $x_{\text{HI}}$ rapidly evolves from $x_{\text{HI}} \ll 1$ at $z \lesssim 6$ to a value of order unity at $z \sim 6$–7, which is broadly consistent with other observational constraints on the reionization history.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — methods: numerical

1. INTRODUCTION

In the cold dark matter (CDM) models of structure formation, structures are formed and grow hierarchically via gravitational instability; subgalactic clumps are formed in CDM halos, and they subsequently merge and collapse to grow into more massive galaxies. The ionizing radiation emitted from massive stars in primeval galaxies should lead to prominent reionization, structures are formed and grow hierarchically via gravitational instability; subgalactic clumps are formed in CDM halos, and they subsequently merge and collapse to grow into more massive galaxies. Therefore, as predicted by Partridge & Peebles (1967), detecting these Lyα emissions via narrow- or intermediate-band imaging is one of the most powerful technique for seeking high-z young star forming galaxies. In the last decade, many Lyα emitters (LAEs), which seem to be powered by star formation activities, have been found through this technique (e.g., Cowie & Hu 1998; Hu et al. 1998; Rhoads et al. 2000; Taniguchi et al. 2005; Shimasaku et al. 2006; Iye et al. 2006; Murayama et al. 2007). The Lyα luminosity functions (LFs) of the LAEs are one of the most fundamental observational quantities and they are becoming more firmly confirmed because of the increase of the survey fields and available samples. Through comparison between the observed LFs and theoretical models of the LAEs, we should be able to obtain important information for LAEs, and more generally, for galaxy formation.

Nevertheless, theoretical understanding of LAEs is still developing, and there are several different approaches for the theoretical modelling: analytical calculations based on the halo mass function and on simple assumptions linking Lyα emission to halo mass (Haiman & Spaans 1999; Thommes & Meisenheimer 2005; Dijkstra et al. 2007b; Mao et al. 2006; Stark et al. 2007a), cosmological hydrodynamic simulations (Barton et al. 2004; Davé et al. 2006; Nagamine et al. 2006; Tassis 2006), and hierarchical clustering models of galaxy formation (so-called semi-analytic models; Le Delliou et al. 2005, 2006). A key ingredient of the theoretical modelling is the escape fraction of the Lyα photons from their host galaxy, $f_{\text{esc, Ly}\alpha}$. In order to predict it precisely, a detailed calculation of radiative transfer of the Lyα photons in realistic matter distribution in a galaxy is required (e.g., Hansen & Oh 2006). However, such procedure costs huge computational time because of the resonant scatterings of Lyα photons in a galaxy (Neufeld 1990; Charlot & Fall 1993) and a direct comparison to the observed LFs is difficult. Therefore, previous studies for LAE LFs introduced simple phenomenological prescriptions. Le Delliou et al. (2005, 2006) and Dijkstra et al. (2007b) assumed a constant and universal escape fraction regardless of the physical properties of galaxies. Mao et al. (2006) adopted screen-type interstellar dust attenuation, but a detailed merger history of dark haloes in hierarchical clustering was not taken into account.

Fortunately, there are some hints for the physical properties of LAEs from observations. Lyα emitting galaxies in the nearby universe generally have low metallicity or small dust amount (Charlot & Fall 1993) and show evidence for outflow or galactic wind (Lequeux et al. 1995; Kunth et al. 1998, 2003; Mas-Hesse et al. 2003; Keel 2005). These properties are also found in high-z Lyman-break galaxies (LBGs) show-
ing strong Lyα emission (Pettini et al. 2002; Shapley et al. 2003; Bower et al. 2004; Wilman et al. 2005; Frye et al. 2007; Pentericci et al. 2007; Swinbank et al. 2007; Tapken et al. 2007). It is theoretically quite reasonable to expect that the amount of metal or dust and existence of galaxy-scale outflow strongly affect the emergent luminosity of Lyα emission. Because of the resonant scattering by H I, Lyα photons have a much longer path to diffuse out from a galaxy than UV continuum photons, and hence they are even more vulnerable to the absorption by dust. On the other hand, outflows would result in a velocity difference between H I gas and Lyα photons, and hence the escape of a Lyα photon would become easier. Therefore, these observations and theoretical considerations indicate that the universal and constant $f_{\text{esc}}^{\text{Ly}\alpha}$ in all galaxies is oversimplified, and a more realistic modeling of $f_{\text{esc}}^{\text{Ly}\alpha}$ is worth investigated.

Another hint for the value of $f_{\text{esc}}^{\text{Ly}\alpha}$ comes from direct observational estimates. Gawiser et al. (2006) reported observational estimates of $f_{\text{esc}}^{\text{Ly}\alpha}$ for LAEs at $z = 3.1$ as $f_{\text{esc}}^{\text{Ly}\alpha} \sim 0.8$ (the best fit) and an lower limit of $f_{\text{esc}}^{\text{Ly}\alpha} \gtrsim 0.2$. However, the semi-analytic prediction by Le Delliou et al. (2005, 2006) requires a much smaller value of $f_{\text{esc}}^{\text{Ly}\alpha} = 0.02$ to fit the observed LAE LFs. Therefore a new model of LAE LFs that can reproduce the observations with $f_{\text{esc}}^{\text{Ly}\alpha} \sim 1$ is highly desirable.

Here, we present a new model of LAE Lyα LFs, based on a semi-analytic model of hierarchical galaxy formation (a slightly updated version of Nagashima & Yoshii 2004, used in Nagashima et al. 2004). This Mitaka model is one of the latest semi-analytic models in which the merger history of dark matter haloes is taken into account and baryon physics such as star formation and feedback is phenomenologically treated (e.g., Kauffmann et al. 1993; Cole et al. 1994; Nagashima et al. 1999; Somerville &Primack 1999; Nagashima & Yoshii 2004; Baugh et al. 2005; Nagashima et al. 2005). This model can reproduce most of the observations for photometric, kinematic, structural, and chemical properties of local galaxies. Moreover, the LFs and angular two-point correlation functions of LBGs at $z = 4$ and 5 predicted by this model coupled with N-body simulations are found to be in good agreement with the observation (Kashikawa et al. 2006a). We extend this model to treat LAEs, but without changing any original parameters determined by the fit to observations. Rather, we try to explain the LAE LFs by minimal extension with a least number of new and physically-motivated parameters. Specifically, we incorporate two new effects in the calculation of $f_{\text{esc}}^{\text{Ly}\alpha}$: Lyα photon extinction by dust and galactic wind driven by the supernova feedback. The new model will be carefully compared with all currently available data of high redshift LAE LFs.

The observed number of LAEs would be significantly reduced if the intergalactic medium (IGM) is neutral, because the red wing of the Gunn-Peterson trough should attenuate the Lyα emission (e.g., Miralda-Escudé 1998; Haiman & Spaans 1999). Therefore, the apparent evolution of LAE LF is recognized as an invaluable probe of the cosmic reionization, and this approach has already been applied to the observed data (Rhoads & Malhotra 2001; Haiman 2002; Malhotra & Rhoads 2004; Stern et al. 2005; Kashikawa et al. 2006; Iye et al. 2006) to constrain the reionization history, which is complementary to the spectra of quasars (Fan et al. 2006) or gamma-ray burst (GRB) afterglows (Totani et al. 2006). However, a weak point of the LAE-LF method is a degeneracy between the intrinsic evolution of the LAE LFs and the apparent evolution by the IGM effect. Therefore, the intrinsic LF evolution must be known reliably to derive a robust constraint on the reionization. However, an ad hoc assumption of no intrinsic evolution was invoked in most of previous studies. We will discuss some implications for reionization based on our results of LAE LF evolution.

The rest of this paper is organized as follows. In §2 we describe our extension of the Mitaka model to incorporate LAEs, and we compare the model results with the observed LAE LFs at various redshifts in §3. We discuss implications for reionization in §4, and then summarize this work in §5. The background cosmology adopted in this paper is the standard ΛCDM model: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.04$, $h = 0.7$, and $\sigma_8 = 0.9$.

2. MODEL DESCRIPTION

The detailed description of the Mitaka semi-analytic model for hierarchical galaxy formation is given in Nagashima & Yoshii (2004) (see also Nagashima et al. 2005). Here we focus on the extension of the original Mitaka model to include LAEs.

2.1. Star Formation Rate in Starburst Galaxies

In the original Mitaka model, all of the cold gas in a galaxy turns into stars and hot gas instantaneously when the galaxy is classified as a “starburst” as a result of a major merger, and hence the SFR cannot be defined. This means that we cannot calculate the Lyα photon production rate appropriately that is essential to determine the Lyα luminosity. However, starburst galaxies could have a significant contribution to LAE LFs, because they have the highest SFR. Therefore we modify the Mitaka model to calculate SFR in starburst populations; we adopt an exponential SFR evolution with a time scale of $\tau_{\text{burst}}$:

$$\psi(t) = \frac{M_0^{\text{cold}}}{\tau_{\text{burst}}} \exp \left( -\frac{t}{\tau_{\text{burst}}} \right),$$

where $M_0^{\text{cold}}$ is the initial mass of available cold gas for star formation. We make a reasonable assumption that $\tau_{\text{burst}}$ is proportional to the dynamical time of the newly formed spheroid, as $\tau_{\text{burst}} = f_{\text{burst}} \tau_{\text{dyn}}$. We adopt $f_{\text{burst}} = 10$, which is consistent with SPH simulations (e.g., Kobayashi 2005) and with a recent observation of submillimeter galaxies at $z \sim 2$–3 (Tacconi et al. 2006).

It is expected that not all of the cold gas will be locked up into stars, but some fraction of gas will be heated by supernova feedback, and then ejected from a galaxy as a hot galactic wind. This effect has already been taken into account in the Mitaka model, to reproduce various scaling laws of local galaxies. We define the efficiency of star formation $f_s$ as $M_* = f_s M_0^{\text{cold}}$, where $M_*$ is the finally produced stellar mass after the starburst episode. The parameter $f_s$ is determined by the Mitaka model, and it depends on the dark halo circular velocity $V_c$, since the feedback should be more efficient for less massive (smaller $V_c$) galaxies from which gas can be more easily removed.²

Since the galactic wind will blow up the ISM gas and stop the star formation, it is reasonable to identify the time of onset of the galactic wind, $t_{\text{wind}}$, as that when the stellar mass

² The quantity $f_s(V_c)$ scales as $\propto V_c^4$ and $\propto V_c^3$ for $V_c \lesssim V_*$ and $\gtrsim V_*$, respectively, where $V_* \sim 130$ km/s (Nagashima & Yoshii 2004).
produced by the above SFR evolution becomes \( f_s M_{\text{cold}} \), i.e.,

\[
\int_0^{t_{\text{end}}} \psi(t) \, dt = f_s M_{\text{cold}},
\]

and hence \( t_{\text{wind}} = -t_{\text{burst}} \ln(1 - f_s) \). This indicates that the galactic wind phase will onset later for massive galaxies, and this trend is similar to the traditional picture of the galactic wind in starbursts (Arimoto & Yoshii 1987). After the onset of the galactic wind, star formation is stopped and the interstellar gas will escape from a galaxy with a time scale of \( t_{\text{esc}} = r_*/v_r \), where \( r_* \) is the effective radius of the galaxy calculated in the Mitaka model.

### 2.2. Observed Line Luminosity of Ly\(\alpha\)

Let \( L_{\text{Ly}\alpha} \) be the Ly\(\alpha\) line luminosity emitted from a galaxy, which is given by

\[
L_{\text{Ly}\alpha} = L_{\text{Ly}\alpha}^{\text{max}} \left( 1 - f_{\text{LyC}} \right) f_{\text{Ly}\alpha} \]

(3)

where \( f_{\text{LyC}} \) and \( f_{\text{Ly}\alpha} \) are the escape fraction of H I ionizing photons and Ly\(\alpha\) photons from their host galaxy, respectively. We adopt \( f_{\text{LyC}} = 0 \), i.e., all ionizing photons emitted from massive stars are absorbed in their host galaxy. Although this assumption may be rather extreme, it is a reasonable treatment for our purpose because the observationally inferred value of \( f_{\text{LyC}} \) is much less than the unity (Inoue et al. 2006). The modelling of \( f_{\text{Ly}\alpha} \) is the key issue of this work, and will be treated in detail in the next subsection.

The maximally possible luminosity \( L_{\text{Ly}\alpha}^{\text{max}} \) is the luminosity that is achieved if all H I ionizing photons emitted from massive stars are absorbed by H I in the ISM (i.e. \( f_{\text{LyC}} = 0 \)) and then reprocessed into Ly\(\alpha\) photons in the ionization equilibrium. We define \( \eta_{\text{Ly}\alpha} \) as the expected number of Ly\(\alpha\) photons produced by one ionizing photon (or equivalently, by one recombination); in the case A recombination it is given by \( \eta_{\text{Ly}\alpha} = \alpha_{\text{Ly}\alpha} / \alpha_A = 0.40 \) and in the case B, it becomes \( \eta_{\text{Ly}\alpha} = (\alpha_{\text{Ly}\alpha} - \alpha_{\text{Ly}\alpha}^0) / \alpha_A = 0.68 \) (Osterbrock 1989, §4.2 and 11.8). Here, \( T = 10^4 \) K is assumed in both cases. We apply the case B following the previous studies (e.g., Charlot & Fall 1993; Valls-Gabaud 1993; Haiman & Spaans 1999; Le Delliou et al. 2005, 2006; Mao et al. 2006; Tasitsiomi 2006; Dijkstra et al. 2007b; Stark et al. 2007a), but the luminosity would not be changed significantly even if we apply the case A. Note that the case A may be appropriate for the situation of \( f_{\text{Ly}\alpha} \sim 1 \).

Then, for a quiescent galaxy in which star formation time scale is much longer than the massive star lifetime, \( L_{\text{Ly}\alpha}^{\text{max}} \) is given by

\[
L_{\text{Ly}\alpha}^{\text{max}}(t) = \eta_{\text{Ly}\alpha} \varepsilon_{\text{Ly}\alpha} \psi(t) Q_{\text{HI}}^{\text{quies}}(Z_{\text{cold}}),
\]

(4)

where \( \varepsilon_{\text{Ly}\alpha} = h\nu_{\text{Ly}\alpha} = 10.2 \text{ eV} \) and \( Q_{\text{HI}}^{\text{quies}} \) is the ionizing photon emission rate normalized by a unit SFR. On the other hand, star formation time scale could be comparable with the massive star lifetime in starburst galaxies, and we must take into account the evolution of ionizing photon production rate in stellar evolution. Then we calculate as

\[
L_{\text{Ly}\alpha}^{\text{max}}(t) = \eta_{\text{Ly}\alpha} \varepsilon_{\text{Ly}\alpha} \int_0^t \psi(t) Q_{\text{HI}}^{\text{quies}}(t - t', Z_{\text{cold}}) \, dt',
\]

(5)

where \( Q_{\text{HI}}^{\text{quies}}(t, Z_{\text{cold}}) \) is the ionizing photon production rate from an unit stellar mass whose age is \( t \). Note that the physical dimensions of \( Q_{\text{HI}}^{\text{quies}} \) and \( Q_{\text{HI}}^{\text{burst}} \) are different. These quantities are calculated from the result of Schaerer (2003) with a correction for the initial mass function used in the Mitaka model. Both \( Q_{\text{HI}}^{\text{quies}} \) and \( Q_{\text{HI}}^{\text{burst}} \) increase by a factor of \( \sim 3 \) with decreasing stellar metallicity from the solar abundance to the zero metallicity. The stellar metallicity is calculated from that of the cold gas, \( Z_{\text{cold}} \), in the Mitaka model. The evolution of \( Q_{\text{HI}}^{\text{burst}}(t) \) is characterized by the two phases: almost constant phase at \( Q_{\text{HI}}^{\text{burst}} \sim 10^{47} \) photons s\(^{-1}\) M\(_\odot\)^{-1} for \( t \lesssim 10^6 \) yr and the subsequent exponential decay with a typical timescale of several million years.

Finally, when the IGM neutrality is high, Ly\(\alpha\) luminosity could be reduced by IGM absorption, and we include this effect as:

\[
I_{\text{obs}} = L_{\text{Ly}\alpha} \eta_{\text{Ly}\alpha},
\]

(6)

where \( I_{\text{Ly\alpha}} \) is the IGM transmission to Ly\(\alpha\) photons, and it is set to be unity except for \( z \gtrsim 6 \), since \( I_{\text{Ly\alpha}} \sim 1 \) has been established at \( z \lesssim 6 \) by observations (Fan et al. 2006).

### 2.3. Ly\(\alpha\) Escape Fraction Modelling

We first examine the following simple models for \( f_{\text{Ly}\alpha} \):

- the simply proportional model: \( f_{\text{Ly}\alpha} = f_0 \),
- the dust (screen) model: \( f_{\text{Ly}\alpha} = f_0 e^{-x} \),
- the dust (slab) model: \( f_{\text{Ly}\alpha} = f_0 (1 - e^{-x}) / x \),

where \( x = N_{\text{cold}} Z_{\text{cold}} / (N_{\text{cold}} Z_{\text{cold}}) \) and \( N_{\text{cold}} \) is column density of cold gas that is computed from the cold gas mass \( M_{\text{cold}} \) and the effective radius \( r_* \), so \( N_{\text{cold}} \equiv (M_{\text{cold}} / 2) / \pi r_*^2 \). The simple proportional model assumes an universal and constant value of \( f_{\text{Ly}\alpha} \) for all galaxies, as assumed in Le Delliou et al. (2005, 2006). The parameter \( (N_{\text{cold}} Z_{\text{cold}}) \) determines the strength of the absorption of Ly\(\alpha\) by dust. The absorption of UV continuum by dust has already been included in the Mitaka model, but we treat this parameter independently for the Ly\(\alpha\) absorption by dust, since the effective optical depth for the Ly\(\alpha\) photons could be much larger than that for continuum photons because of much longer path caused by multiple resonant scattering of Ly\(\alpha\) photons by neutral hydrogen.

Furthermore, we examine another \( f_{\text{Ly}\alpha} \) model that incorporates the impact of galaxy-scale outflow in addition to that of the interstellar dust extinction, which we call the outflow+dust model. In this model, starburst galaxies are classified into three phases of pre-outflow, outflow, and post-outflow phases. These phases are defined by the elapsed time \( t \) from the onset of star formation, as \( t < t_{\text{wind}} \), \( t_{\text{wind}} \leq t < t_{\text{wind}} + t_{\text{esc}} \), and \( t \geq t_{\text{wind}} + t_{\text{esc}} \), respectively (see § 2.1 for the definition of \( t_{\text{wind}} \) and \( t_{\text{esc}} \)). All the quiescently star-forming galaxies are classified into the pre-outflow phase. We model \( f_{\text{Ly}\alpha} \) in the outflow+dust model as follows:

- the pre-outflow phase: \( f_{\text{Ly}\alpha} = f_0 e^{-x} \),
- the outflow phase: \( f_{\text{Ly}\alpha} = f_0 \),
- the post-outflow phase: \( f_{\text{Ly}\alpha}^{\text{out}} = 0 \).

In the pre-outflow phase, we adopt the same modeling as the above dust models. We only apply the screen dust prescription because the difference between the screen and slab dust models is small, as we will find in § 3. In the outflow phase, according to the theoretical expectation that outflow could drastically decrease the effective opacity for Ly\(\alpha\) photons, we
adopt \( f_{0}^{\text{ind}} = 0.8 \) as inferred for observed LAEs (Gawiser et al. 2006). Note that we do not treat \( f_{0}^{\text{ind}} \) as a free parameter, keeping the number of free parameters same as the dust models. In the post-outflow phase, while the H I ionizing photons are produced at moderate rates, neutral gas to absorb these photons in host galaxies is absent (i.e., \( f_{\text{esc}}^\alpha = 1 \)), and hence no Ly\( \alpha \) photons are produced (\( f_{\text{esc}}^{\text{Ly} \alpha} = 0 \)).

Therefore, the new free parameters in all the above models are \( f_{0} \) and \( (N_{\text{cold}}/Z_{\text{cold}})_{0} \), while all other parameters are from the original Mitaka model without changing their values.

### 2.4. Luminosity Function of LAEs

Now we can calculate the \( \text{Ly} \alpha \) LF of LAEs by calculating \( L_{\text{Ly} \alpha}^{\text{br}} \), as explained above from the Mitaka model of galaxy formation. We determine the free parameters of \( f_{\text{esc}}^{\text{Ly} \alpha} \) models by fitting the model Ly\( \alpha \) LF with \( T_{\text{Ly} \alpha}^{\text{GVM}} = 1 \) to the data at \( z = 5.7 \) reported by Shimasaku et al. (2006), which is corrected for both detection completeness and contamination, being the most reliable LAE LF to date. Specifically, we perform a \( \chi^2 \) test in the whole observational range of the Ly\( \alpha \) luminosity (log [\( (h^{-2} \text{ergs s}^{-1}) \] = 42.1–43.1)). Because the LF error bars are the smallest at the faint end, the free parameters of \( f_{\text{esc}}^{\text{Ly} \alpha} \) are determined mainly by matching to the faint-end of the Ly\( \alpha \) LF of Shimasaku et al. We fix these values of the free parameters at \( z = 5.7 \) and then apply the model to the data at other redshifts with keeping the parameter values, because they should reflect the physical properties of Ly\( \alpha \) photons that are not expected to evolve with redshift.

It should be noted here that we do not set any criterion on the equivalent width (EW) of Ly\( \alpha \) lines for model galaxies to be selected as LAEs. Though the observations of LAEs usually set threshold values for EW in the selection, the effect of different EW thresholds on the predicted Ly\( \alpha \) LF is small. We show the model calculation of Ly\( \alpha \) EW distribution of LAEs at \( z = 5.7 \) in Figure 1, which is intrinsic EW and the IGM absorption effect on the continuum is not taken into account. Here, we calculated the EW by \( L_{\text{Ly} \alpha} \) and the continuum luminosity of model galaxies. Almost all LAEs have larger EWs than a typical threshold in observation, i.e., EW_{\text{test}}(Ly\( \alpha \)) = 20 \( \AA \), and hence our results do not change even if we set a threshold Ly\( \alpha \) EW used in observations. This result is consistent with that of Le Delliou et al. (2006).

### 3. RESULTS

#### 3.1. Luminosity Functions at \( z \lesssim 6 \)

We first compare the simplest model (the simply proportional model) to the cumulative Ly\( \alpha \) LF data at \( z = 5.7 \) in Figure 2. The best-fit is \( f_{0} = 0.60 \), and this model overpredicts the bright-end of the LAE LF. We see from the top panel of Figure 2 that the dominant component at the bright-end of the Ly\( \alpha \) LF is the starburst galaxies, while the quiescently star forming galaxies dominate at the faint end. If we try to adjust the model to the bright end, we must assume a much lower value of \( f_{\text{esc}}^{\text{Ly} \alpha} \ll 1 \) than the observationally inferred value by Gawiser et al. (2006). This could be one of the possible reasons that Le Delliou et al. (2005, 2006) obtained \( f_{\text{esc}}^{\text{Ly} \alpha} \ll 1 \) with the same treatment for \( f_{\text{esc}}^{\text{Ly} \alpha} \), though their model is completely independent of our own and a clear comparison is not easy.

The middle and bottom panels show that the starburst galaxies in the pre-outflow phase having high metal column densities (\( N_{\text{cold}}Z_{\text{cold}} \gtrsim 10^{21} \) Z\(_{\odot} \) cm\(^{-2} \)) dominate in the largest luminosity range. This is reasonable since the most efficient Ly\( \alpha \) photon production is expected during young stage of the starburst, and the galaxies in such phase are expected to be gas and metal rich. This result indicates that the effect of interstellar dust extinction in \( f_{\text{esc}}^{\text{Ly} \alpha} \) models would reduce the number of LAEs at the bright end, in a direction to a better agreement with observations.

We then show the dust models and the outflow+dust model in Figure 6. The fitted values of the model parameters are tabulated in Table 1. As expected, the number of the luminous LAEs drastically decreases in the dust models. However, it can be seen that this effect is too strong, and the sharp drop of LAE number at the bright end does not match well to the observed Ly\( \alpha \) LFs. In contrast, the outflow+dust model well reproduces the observed Ly\( \alpha \) LFs in the whole range of Ly\( \alpha \) luminosity shown in Figure 6. It should be noted again that the number of free model parameters is the same for the dust and outflow+dust models. LAEs at the bright-end are dominated by galaxies in the outflow phase, which is consistent with the observational indications of outflows. Furthermore, \( f_{\text{esc}}^{\text{Ly} \alpha} \sim 0.8 \) has been assumed for the outflowing LAEs, which is consistent with a recent observational estimate for LAEs at \( z \approx 3.1 \) by Gawiser et al. (2006).

#### 3.2. Luminosity Functions at \( z \gtrsim 6 \) and IGM transmission

Turning now to the Ly\( \alpha \) LFs at redshift beyond 6 when the reionization is believed not to have ended yet. In contrast to the agreement at the lower redshifts, all \( f_{\text{esc}}^{\text{Ly} \alpha} \) models assuming \( T_{\text{Ly} \alpha}^{\text{GVM}} = 1 \) with the same parameters determined at \( z = 5.7 \) overpredict the number of the LAEs at \( z = 6.56 \) compared with the observational data reported by Kashikawa et al. (2006b), as presented in the top panel of Figure 4. This discrepancy can be resolved if we adopt a simple prescription of luminosity-independent IGM transmission that is less than the unity (\( T_{\text{Ly} \alpha}^{\text{GVM}} \sim 0.6–0.8 \)); the predicted Ly\( \alpha \) LFs with \( T_{\text{Ly} \alpha}^{\text{GVM}} = 0.8 \) and 0.6 are shown in the middle and bottom panels, respectively, in Figure 7. We also show the predicted Ly\( \alpha \) LFs at an even higher redshift of \( z = 6.96 \) in Figure 5. Though the statistics is obviously insufficient, the most distant galaxy found so far (Iye et al. 2006) indicates \( T_{\text{Ly} \alpha}^{\text{GVM}} \lesssim 0.7 \). We will discuss the implications for the reionization history from these results in §4.

#### 3.3. Interpretations for Intrinsic Ly\( \alpha \) LF Evolutionary Features

We show the intrinsic (i.e., \( T_{\text{Ly} \alpha}^{\text{GVM}} = 1 \)) evolution of the cumulative Ly\( \alpha \) LF in the outflow+dust model from redshift \( z = 3.6 \) to 8.8 in Figure 5. It is also interesting to compare this evolution with that of the dark halo mass function, since a number of previous studies predicted LAE LF evolution based on the halo mass function. This is shown in Fig. 7 using the halo mass function given by Yahagi et al. (2004, hereafter YNY) that is used in the Mitaka model. Here, we adopt \( M_{\text{DM}}/L_{\text{Ly} \alpha} = 160 \) M\(_{\odot} / L_{\odot} \), where \( L_{\odot} \) is the bolometric solar luminosity.

A clear trend of the LAE LF evolution is that the characteristic luminosity where the LFs have a break, \( L_{\text{br}} \), is similar to that of the dark halo mass function. Therefore, a mecha-
nism that keeps the brightest Lyα luminosity almost constant against redshift would explain these trends.

Such a mechanism is likely to be a combination of the dust extinction and outflow effect. The comparison of the dust and dust-outflow models with the simply proportional model (Figs. 2 and 3) indicates that galaxies more massive than a critical mass scale cannot become bright LAEs because of heavy extinction by a large amount of gas and metals, and/or because of the large gravitational potential that prevents an efficient outflow. Therefore, even if the number of galaxies more massive than the critical mass scale should increase significantly with time by hierarchical structure formation, the mass of the brightest LAEs does not significantly evolve. This interpretation can be tested by estimating the mass of LAEs in future observations.

4. IMPLICATIONS FOR COSMIC REIONIZATION

The requirement of $T_{\text{Ly}\alpha}^{\text{IGM}} < 1$ to reproduce the observed Lyα LFs at $z \gtrsim 6$ suggests that the IGM opacity for the Lyα emission rapidly increases beyond $z \sim 6$. From the value of $T_{\text{Ly}\alpha}^{\text{IGM}}$ estimated in our analyses, we can estimate the IGM neutral fraction $x_{\text{HI}} \equiv n_{\text{HI}}/n_{\text{H}}$. Unfortunately, this procedure is highly complicated because there are many physical processes that must be considered in calculation of the attenuation factor of Lyα line luminosity (Santos 2004; Dijkstra et al. 2007a). Here, we apply the dynamic model with a reasonable velocity shift of Lyα line by 360 km/s redward of the systemic velocity (the dashed curve of Figure 25 in Santos 2004).

The reason for the choice of this particular model is that it predicts no attenuation when $x_{\text{HI}} = 0$. Note that some other models of Santos (2004) predict a significant attenuation even in the case of $x_{\text{HI}} = 0$, due to the neutral gas associated with the host haloes of LAEs. Choosing this model then means that we ascribe the sudden strong evolution of the Lyα LF at $z \gtrsim 6$ only to the absorption by pure IGM. We consider that this is a reasonable assumption, since observations indicate that the escape fraction of Lyα photons is about unity at least for LAEs at $z \sim 3$ (Gawiser et al. 2006). If LAEs at $z \sim 7$ are a similar population to the low-$z$ LAEs, we do not expect significant absorption by neutral gas physically associated to LAEs. It should also be noted that the brightest LAEs in our model LFs are in the outflow phase, and we may not expect a large amount of neutral gas around them.

For the range of $T_{\text{Ly}\alpha}^{\text{IGM}} = 0.6 - 0.8$ at $z = 6.56$ estimated from the outflow+dust model, we find $x_{\text{HI}} \sim 0.25 - 0.35$. At $z = 6.9$, our constraint of $T_{\text{Ly}\alpha}^{\text{IGM}} \lesssim 0.7$ translates into $x_{\text{HI}} \gtrsim 0.3$. On the other hand, it should also be kept in mind that if $z \sim 7$ LAEs are surrounded by a significant amount of nearby neutral gas that is not present for LAEs at $z \sim 3$, the estimate of $x_{\text{HI}}$ as an average of IGM in the universe could become lower than those derived here.

Although the translation from $T_{\text{Ly}\alpha}^{\text{IGM}}$ into $x_{\text{HI}}$ is model dependent, it should be noted that our model overpredicts the observed LAE LFs rather suddenly beyond $z \sim 6$, while it reproduces well the observed LAE LFs at $z \lesssim 6$ without invoking the absorption in IGM. We suggest that this is an evidence for significant absorption by neutral IGM at $z \gtrsim 6$, and it requires $x_{\text{HI}}$ of order unity. This is broadly consistent with the recent constraints by other methods (Fan et al. 2006). Here we emphasize that there has been no strong "positive" evidence for a considerable amount of IGM neutral hydrogen ($x_{\text{HI}}$ of order unity) at $z \gtrsim 6$; quasar Gunn-Peterson tests give only a weak lower limit of $x_{\text{HI}} \gtrsim 10^{-3}$ (Fan et al. 2006) and the GRB 050904 gives only an upper limit of $x_{\text{HI}} \lesssim 0.6$ (Totani et al. 2006).

For the future studies of reionization through LAE LFs, we plot the LF evolution of the outflow+dust model from $z = 3.6$ to $z = 8.8$ in Figure 6 with $T_{\text{Ly}\alpha}^{\text{IGM}} = 1$. The redshifts of 7.7 and 8.8 correspond to the next windows that are relatively free of bright OH lines at wavelengths of 1.06 µm and 1.19 µm, respectively. There are already several pioneering works, such asWillis & Courbin (2005), Cuby et al. (2007) and Stark et al. (2007b). Moreover, other wide-field imagers with narrow-band filters to search the redshifted Lyα emission at these wavelengths will be available on 4 m or 8-10 m class telescopes in the near future (see, e.g. Cuby et al. 2007, for more detail). Our predicted LAE LF evolution would be useful for the planning of the future LAE surveys, and it can also be used as a guide to derive $T_{\text{Ly}\alpha}^{\text{IGM}}$ from the observed LAE LFs$^3$.

5. CONCLUSIONS

We constructed a new theoretical model for Lyman alpha emitters at high-$z$ based on a hierarchical clustering model of galaxy formation (the Mitaka model), taking into account physical effects of dust absorption and galaxy-scale outflow in calculation of Lyα photon escape fraction ($f_{\text{esc}}^{\text{Ly}\alpha}$) from host galaxies. We introduced just two new parameters based on some physical considerations to include these two effects, while we kept unchanged the original model parameters of the Mitaka model that have been tuned to reproduce a number of observations of local galaxies.

The observed Lyα LFs of LAEs at several redshifts in $z \lesssim 6$ are reproduced well by our model assuming completely ionized IGM (the IGM transmission $T_{\text{Ly}\alpha}^{\text{IGM}} = 1$). Especially, it has been known that the LAE LFs show very little evolution in $z \sim 3-6$ compared with the dark halo mass function, and our model can naturally explain this by the above effects newly included in this work. The escape fraction of Lyα photons from LAEs in our model is $f_{\text{esc}}^{\text{Ly}\alpha} \sim 0.8$, which is consistent with a recent observational estimate. Moreover, our model predicts that the bright-end of the Lyα LF is dominated by the starburst galaxies in the phase of galaxy-scale outflow driven by the supernova feedback. This is also consistent with the observational results for local and high-$z$ galaxies with strong Lyα emission. On the other hand, the simple model with a constant and universal $f_{\text{esc}}^{\text{Ly}\alpha}$ requires $f_{\text{esc}}^{\text{Ly}\alpha} \ll 1$ in order not to overproduce the brightest LAEs. This is consistent with a previous theoretical study that invoked the same assumption, but the required $f_{\text{esc}}^{\text{Ly}\alpha} \sim 0.8$ value is considerably lower than the observed values.

In contrast to the success at $z \lesssim 6$, our model overpredicts the LAE LF beyond $z \gtrsim 6$, and we interpret this as a result of Lyα attenuation by neutral hydrogen in IGM. We found that a simple prescription of luminosity-independent $T_{\text{Ly}\alpha}^{\text{IGM}}$ is sufficient to explain the observed LAE LFs; the LF at $z = 6.56$ is reproduced with $T_{\text{Ly}\alpha}^{\text{IGM}} = 0.6 - 0.8$, and that at $z = 6.9$ indicates $T_{\text{Ly}\alpha}^{\text{IGM}} \lesssim 0.7$. Though it is not straightforward to derive the IGM neutral fraction $x_{\text{HI}}$ from these results, the discrepancy in the case of $T_{\text{Ly}\alpha}^{\text{IGM}} = 1$ appears rather suddenly beyond $z \gtrsim 6$ compared with the results in $z \lesssim 6$. Therefore we suggest that this gives an evidence for a rapid evolution of $x_{\text{HI}}$ from $x_{\text{HI}} \lesssim 1$ at $z \lesssim 6$ to a value of order unity at $z \gtrsim 6$. This

$^3$ The numerical data of the LF evolution is available on request to the authors.
positive evidence for a significant abundance of neutral hydrogen in IGM is complementary to the constraints obtained by other methods based on quasar and GRB spectra.

Our theoretical model for the LAE LF evolution would be helpful for planning a LAE survey and for interpretation of the observed Lyα LF at even higher redshifts in the future studies. Further investigation of various properties (e.g., spectral energy distribution, mass, or spatial clustering) of LAEs in our model and comparison with observations will be done in our future studies.

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TABLE 1
THE BEST-FIT MODEL PARAMETERS OF Lyα PHOTON ESCAPE FRACTION.

| $f_{\text{esc}}^\text{Lyα}$ model | $f_0$  | $(N_{\text{cold}}Z_{\text{cold}})_{0}$ [$10^{20}$ Z$_\odot$ cm$^{-2}$] |
|----------------------------------|------|--------------------------------------------------|
| simply proportional.............| 0.60$^{+0.05}_{-0.05}$ | ... |
| dust (screen)......................| 0.67$^{+0.04}_{-0.04}$ | 6.0$^{+2.7}_{-1.7}$ |
| dust (slab).......................| 0.80$^{+0.05}_{-0.05}$ | 2.4$^{+1.7}_{-1.7}$ |
| outflow+dust......................| 0.68$^{+0.04}_{-0.04}$ | 4.2$^{+1.5}_{-1.5}$ |

NOTE. — The errors are statistical 1σ as a result of the fit to the Lyα LF of the LAEs at $z = 5.7$ reported by Shimasaku et al. (2006). The screen dust extinction is adopted in the pre-outflow phase of the outflow+dust model.
Fig. 1.— The predicted rest-frame EW of the Ly\(\alpha\) emission line for the LAEs at \(z = 5.7\) in the outflow+dust model, decomposed into three intervals of Ly\(\alpha\) luminosity. The EWs are intrinsic without IGM absorption for Ly\(\alpha\) or UV continuum flux. The thin and thick histograms are the EW distributions for quiescent and starburst galaxies, respectively. The vertical dotted line represents a typical threshold for galaxies to be selected as LAEs in observation.
Fig. 2.— The cumulative Lyα LF of the simply proportional model at $z = 5.7$ with $f_0 = 0.60$. Top: The contributions from quiescent and starburst galaxies are shown separately, as indicated in the figure. The symbols with error bars are observational data of the LAEs at $z = 5.7$. The references for the data points are as follows: Shimasaku et al. (2006), Murayama et al. (2007), Ajiki et al. (2003), Hu et al. (2004), and Rhoads et al. (2003). Note that these observational data are not corrected for detection completeness and contamination, except for Shimasaku et al. (2006). Middle: starburst (thick lines) and quiescent (thin lines) galaxies are further decomposed into two groups corresponding to high (solid lines) and low (dashed lines) values of the metal column density, $N_{\text{cold}}Z_{\text{cold}}$, separated by $N_{\text{cold}}Z_{\text{cold}} = 10^{21} \, [Z_{\odot} \, \text{cm}^{-2}]$. The dotted curve is the total Lyα LF without any decomposition. Bottom: The Lyα LFs of starburst galaxies are shown by thick curves, which are decomposed into the pre-outflow, outflow, and post-outflow phases. The Lyα LF of the quiescent galaxies is shown by the thin dashed line, and the thin dotted line is the total Lyα LF.
The evolution of the cumulative Lyα LFs with redshift at $z \lesssim 6$. The curves show the model results, while the symbols with error bars are the observational data. The four different models of $f_{Ly\alpha}^{esc}$, i.e., the simply proportional, dust (screen), dust (slab), and outflow+dust models are shown (see the top panel for the line markings). The thin solid curve is the contribution from the starbursts in the outflow phase in the outflow+dust model. The references for the data points that were not given in Figure 2 are: Yamada et al. (2005), Gronwall et al. (2007), Gawiser et al. (2006), Kudritzki et al. (2000), Cowie & Hu (1998), Maier et al. (2003), Ouchi et al. (2003), and Santos et al. (2004).
Fig. 4.— The cumulative Lyα LFs at $z = 6.56$. The line-markings are the same as Fig. 3 but with different values of the IGM transmission $T_{\text{Ly}α}^{\text{IGM}} = 1.0$, 0.8, and 0.6 for the top, middle, and bottom panels, respectively. The open squares are the observed data from the photometric sample of Kashikawa et al. (2006b) corrected for detection completeness (an upper limit), while the circles from the pure spectroscopic sample (a lower limit).
Fig. 5. — The same as Fig. 4 but at $z = 6.96$. The data is from Iye et al. (2006).
Fig. 6.— The evolution of the cumulative Lyα LF in the outflow+dust model from redshift $z = 3.6$ to $z = 8.8$, assuming transparent IGM to Lyα photons ($\tau_{\text{IGM}}^{\text{Ly}\alpha} = 1$). The contributions from starburst and quiescent galaxies are presented separately in the bottom panel.
Fig. 7.— A comparison of the evolution of the cumulative Lyα LF in the outflow+dust model (thin curves) with that of the dark halo mass function (thick curves) from redshift $z = 3.6$ to $z = 6.9$. The conversion factor of the halo mass into the Lyα line luminosity, $M_{\text{DM}}/L_{\text{Ly}\alpha} = 160 M_\odot/L_\odot$, is chosen to fit the cumulative Lyα LF at $z = 6.9$. 