WERE PROGENITORS OF LOCAL $L^*$ GALAXIES Ly$\alpha$ EMITTERS AT HIGH REDSHIFT?

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ABSTRACT

The Ly$\alpha$ emission has been observed from galaxies over a redshift span $z \sim 0$–8.6. However, the evolution of high-redshift Ly$\alpha$ emitters (LAEs), and the link between these populations and local galaxies, remains poorly understood. Here, we investigate the Ly$\alpha$ properties of progenitors of a local $L^*$ galaxy by combining cosmological hydrodynamic simulations with three-dimensional radiative transfer calculations using the new ART$^2$ code. We find that the main progenitor (the most massive one) of a Milky-Way-like galaxy has a number of Ly$\alpha$ properties close to those of observed LAEs at $z \sim 2$–6, but most of the fainter ones appear to fall below the detection limits of current surveys. The Ly$\alpha$ photon escape fraction depends sensitively on a number of physical properties of the galaxy, such as mass, star formation rate, and metallicity, as well as galaxy morphology and orientation. Moreover, we find that high-redshift LAEs show blueshifted Ly$\alpha$ line profiles characteristic of gas inflow, and that the Ly$\alpha$ emission by excitation cooling increases with redshift, and becomes dominant at $z \gtrsim 6$. Our results suggest that some observed LAEs at $z \sim 2$–6 with luminosity of $L_{\text{Ly} \alpha} \sim 10^{42}$–$10^{43}$ erg s$^{-1}$ may be similar to the main progenitor of the Milky Way at high redshift, and that they may evolve into present-day $L^*$ galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – large-scale structure of universe –

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1. INTRODUCTION

The Ly$\alpha$ emission from young galaxies can be a powerful probe of the early universe (Partridge & Peebles 1967; Charlot & Fall 1993). Recent narrowband deep imaging surveys using large-aperture telescopes have detected a large number of Ly$\alpha$ emitting galaxies, or Ly$\alpha$ emitters (LAEs), at redshifts $z \gtrsim 3$ (e.g., Hu & McMahon 1996; Cowie & Hu 1998; Steidel et al. 2000; Malhotra & Rhoads 2004; Taniguchi et al. 2005; Kashikawa et al. 2006; Shimak inferred that LAEs tend to be LAEs. One of the important issues in galaxy evolution is how high-redshift LAEs evolve to present-day $L^*$ galaxies.

While high-redshift LAEs have been studied with large samples in the redshift range of $z \sim 2$–6, there is only a limited number of observations on LAEs at $z \lesssim 1$. Some local star-forming galaxies have been studied by various wavelengths and show a complex structure of Ly$\alpha$ and UV continuum (Hayes et al. 2007; Östlin et al. 2009). Atek et al. (2009) showed that the $f_{\text{esc}}$ of local LAEs have a large dispersion, ranging from $\sim 3\%$ to $100\%$. In addition, Deharveng et al. (2008) studied a sample of 96 local LAEs at $z = 0.2$–0.35 from UV space telescope Galaxy Evolution Explorer, and found that these LAEs have similar EW distribution as those at $z = 3.1$. Recently, Cowie et al. (2010) have studied $z \sim 0.3$ LAEs with a larger sample, and showed that these LAEs are more compact, and have lower metallicity than UV-continuum-selected galaxies at the same redshift. In addition, Finkelstein et al. (2009) suggested, from fitting of spectral energy distributions (SEDs), that low-$z$ LAEs are significantly more massive and older galaxies than their high-$z$ counterparts.

One of the important issues in galaxy evolution is how high-redshift LAEs evolve into galaxies in the local universe. Cowie et al. (2007) suggested, from clustering analysis, that most $z = 3.1$ LAEs evolve to present-day galaxies of $< 2.5 L^*$, unlike other populations which typically evolve into more massive galaxies. Moreover, Gual et al. (2010) indicated that LAEs at $z = 2.1$ were building blocks of present-day $L^*$ galaxies such as the Milky Way (MW).

However, the link between high-redshift LAEs and local galaxies, and the probability of these LAEs evolving into present-day $L^*$ galaxies are not well constrained from observations. In order to address these questions, one may use the MW as a local laboratory. Moreover, since Ly$\alpha$ emission has
been detected from the most distant galaxies, understanding of the Lyα properties of the MW progenitors will provide an important clue to the formation of early galaxies. To date, there are only a limited number of theoretical studies on this important issue (e.g., Salvadori et al. 2010; Dayal & Libeskind 2012). Both Salvadori et al. (2010) and Dayal & Libeskind (2012) focused on MW progenitors at \( z \sim 6 \) constructed from semi-analytical merger trees and a cosmological smoothed particle hydrodynamics (SPH) simulation, respectively. They both used the same analytical prescription of Lyα emission in which the intrinsic Lyα luminosity scales linearly with the star formation rate (SFR; Dayal et al. 2008). However, because the Lyα properties depend sensitively on a number of factors, such as the scattering and propagation of the photons in the inhomogeneous medium, the dust content of the gas, the ionization structure, the UV continuum, and the photon escape fraction. Such a complicated process can only be probed by comprehensive Lyα radiative transfer calculations combined with realistic simulation of galaxy formation. As we will show in this work, our detailed Lyα modeling on a high-resolution cosmological simulation produce a number of Lyα properties such as the luminosity functions at different redshifts in good agreement with observations. Moreover, in order to investigate the evolution of LAEs, we need to study the progenitors of the MW at different redshifts systematically, not just at a specific time.

In this paper, we investigate the Lyα properties of MW progenitors over a wide redshift range of \( z \sim 0–10 \), by combing cosmological SPH simulation of a MW-like galaxy from Q. Zhu et al. (2012, in preparation) with three-dimensional radiative transfer (RT) calculations using the newly improved ART3 code by Yajima et al. (2011). Our hydrodynamic simulation includes important physics of both dark and baryonic matter, and has high resolutions to track the formation history of the MW. Our RT calculations include both Lyα resonant scattering and continuum emission, and are done on an adaptive-mesh refinement grid, which covers a large dynamical range and resolves the small-scale structures in high-density region. Interstellar dust is also taken into account to accurately estimate the \( f_{\text{esc}} \) of Lyα photons and UV continuum, and the EWs.

The paper is organized as follows. We describe our cosmological simulation in Section 2, and the RT calculations in Section 3. In Section 4, we present results of the Lyα properties of MW progenitors from redshift 10 to 0, which include the Lyα surface brightness, Lyα luminosity, \( f_{\text{esc}} \), EW and line profile. In Section 5, we discuss the dependence of \( f_{\text{esc}} \) on physical properties, LAE fraction in our galaxy sample, Lyα escaping angle, and the contribution from excitation cooling to Lyα emissivity, and we summarize in Section 6.

2. GALAXY MODEL

The cosmological simulation presented here follows the formation and evolution of an MW-size galaxy and its substructures, as described in detail in Q. Zhu et al. (2012, in preparation). The simulation includes dark matter, gas dynamics, star formation, black hole growth, and feedback processes. The initial condition is originally from the Aquarius Project (Springel et al. 2008), which produced the largest ever particle simulation of a MW-sized dark matter halo. The hydrodynamical initial condition is reconstructed from the original collisionless one by splitting each original particle into a dark matter and gas particle pair, as adopted from Wadezpul & Springel (2011).

The whole simulation falls in a periodic box of \( 100h^{-1}\) Mpc on each side with a zoom-in region of a size \( 5 \times 5 \times 5h^{-3}\) Mpc\(^3\). The spatial resolution is \( \sim 250h^{-1}\) pc in the zoom-in region. The mass resolution of this zoom-in region is \( 1.8 \times 10^4 h^{-1} M_\odot \) for dark matter particles, \( 3 \times 10^5 h^{-1} M_\odot \) for gas, and \( 1.5 \times 10^5 h^{-1} M_\odot \) for star particles. The cosmological parameters used in the simulation are \( \Omega_m = 0.25, \Omega_b = 0.75, \sigma_8 = 0.9, \) and \( h = 0.73, \) consistent with the five-year results of the Wilkinson Microwave Anisotropy Probe (Komatsu et al. 2009). The simulation evolves from \( z = 127 \) to \( z = 0 \).

The simulation was performed using the parallel, N-body/SPH code GADGET-3, which is an improved version of that described in Springel et al. (2001) and Springel (2005). For the computation of gravitational forces, the code uses the “TreePM” method (Xu 1995) that combines a “tree” algorithm (Barnes & Hut 1986) for short-range forces and a Fourier transform particle-mesh method (Hockney & Eastwood 1981) for long-range forces. GADGET implements the entropy-conserving formulation of SPH (Springel & Hernquist 2002) with adaptive particle smoothing, as in Hernquist & Katz (1989). Radiative cooling and heating processes are calculated assuming collisional ionization equilibrium (Katz et al. 1996; Davé et al. 1999). Star formation is modeled in a multi-phase ISM, with a rate that follows the Schmidt–Kennicutt law (Schmidt 1959; Kennicutt 1998). Feedback from supernovae is captured through a multi-phase interstellar medium (ISM) by an effective equation of state for star-forming gas (Springel & Hernquist 2003). The UV background model of Haardt & Madau (1996) is used.

Black hole growth and feedback are also included in our simulation based on the model of Springel et al. (2005b) and Di Matteo et al. (2005), where black holes are represented by collisionless “sink” particles that interact gravitationally with other components and accrete gas from their surroundings. The accretion rate is estimated from the local gas density and sound speed using a spherical Bondi–Hoyle (Bondi 1952; Bondi & Hoyle 1944; Hoyle & Lyttleton 1941) model that is limited by the Eddington rate. Feedback from black hole accretion is modeled as thermal energy, \( \sim 5\% \) of the radiation, injected into surrounding gas isotropically, as described in Springel et al. (2005b) and Di Matteo et al. (2005). This feedback scheme self-regulates the growth of the black hole and has been demonstrated to successfully reproduce many observed properties of local elliptical galaxies (e.g., Springel et al. 2005a; Hopkins et al. 2006) and the most distant quasars at \( z \sim 6 \) (Li et al. 2007). We follow the black hole seeding scheme of Li et al. (2007) and Di Matteo et al. (2008) in the simulation: A seed black hole of mass \( M_{\text{BH}} = 10^5 h^{-1} M_\odot \) was planted in the gravitational potential minimum of each new halo identified by the friends-of-friends group finding algorithms with a total mass greater than \( 10^{10} h^{-1} M_\odot \).

The galaxies in each snapshot above redshift 0 are building blocks of the MW, a present-day \( L^* \) galaxy. We therefore define them as “progenitors” of the MW, and the most massive progenitor at any given time step as the “main progenitor.” In this paper, we explore the Lyα properties of \( \sim 60 \) most massive progenitors of each snapshot for 15 snapshots in the redshift range \( z = 0–10.2 \), which gives a total sample of 941 galaxies.

3. RADIATIVE TRANSFER

The RT calculations are done using the three-dimensional Monte Carlo RT code, All-wavelength Radiative Transfer with Adaptive Refinement Tree (ART3), as recently developed by
Yajima et al. (2011). ART\(^2\) was improved over the original version of Li et al. (2008), and features three essential modules: continuum emission from X-ray to radio, Ly\(\alpha\) emission from both recombination and collisional excitation, and ionization of neutral hydrogen. The coupling of these three modules, together with an adaptive refinement grid, enables a self-consistent and accurate calculation of the Ly\(\alpha\) properties, which depend strongly on the UV continuum, ionization structure, and dust content of the object. Moreover, it efficiently produces multi-wavelength properties, such as the spectral energy distribution and images, for direct comparison with multi-band observations.

The detailed implementations of the ART\(^2\) code are described in Li et al. (2008) and Yajima et al. (2011). Here we focus on the Ly\(\alpha\) calculations and briefly outline the process.

The Ly\(\alpha\) emission is generated by two major mechanisms: recombination of ionizing photons and collisional excitation of hydrogen gas. In the recombination process, we consider ionization of neutral hydrogen by ionizing radiation from stars, active galactic nuclei (AGNs), and UV background, as well as by collisions by high-temperature gas. The ionized hydrogen atoms then recombine and create Ly\(\alpha\) photons via the state transition \(2P \rightarrow 1S\). The Ly\(\alpha\) emissivity from the recombination is

\[
e_{\alpha}^{\text{rec}} = f_{\alpha} \alpha_B h \nu_\alpha n_e n_{\text{H}_1},
\]

where \(\alpha_B\) is the case B recombination coefficient, and \(f_{\alpha}\) is the average number of Ly\(\alpha\) photons produced per case B recombination. Here we use \(\alpha_B\) derived in Hui & Gnedin (1997). Since the temperature dependence of \(f_{\alpha}\) is not strong, \(f_{\alpha} = 0.68\) is assumed everywhere (Osterbrock & Ferland 2006).

The product \(h \nu_\alpha\) is the energy of a Ly\(\alpha\) photon, 10.2 eV.

In the process of collisional excitation, high-temperature electrons can excite the quantum state of hydrogen gas by the collision. Due to the large Einstein A coefficient, the hydrogen gas can occur de-excitation with the Ly\(\alpha\) emission. The Ly\(\alpha\) emissivity by the collisional excitation is estimated by

\[
e_{\alpha}^{\text{coll}} = C_{\text{Ly}\alpha} n_e n_{\text{H}_1},
\]

where \(C_{\text{Ly}\alpha}\) is the collisional excitation coefficient, \(C_{\text{Ly}\alpha} = 3.7 \times 10^{-17} \exp(-h \nu_\alpha/kT) T^{-1/2} \text{erg s}^{-1} \text{cm}^3\) (Osterbrock & Ferland 2006).

Once the ionization structure have been determined, we estimate the intrinsic Ly\(\alpha\) emissivity in each cell by the sum of above Ly\(\alpha\) emissivity, \(e_{\alpha} = e_{\alpha}^{\text{rec}} + e_{\alpha}^{\text{coll}}\).

In RT calculations, dust extinction from the ISM is included. The dust content is estimated according to the gas content and metallicity in each cell, which are taken from the hydrodynamic simulation. The dust-to-gas ratio of the MW is used where the metallicity is of solar abundance, and it is linearly interpolated for other metallicity. We use the stellar population synthesis model of GALAXEV (Bruzual & Charlot 2003) to produce intrinsic SEDs of stars for a grid of metallicity and age, and we use a simple, broken power law for the AGN (Li et al. 2008). A Salpeter (1955) initial mass function (IMF) is used in our calculations.

In this work, we apply ART\(^2\) to the 60 most massive progenitors of each snapshot for 15 snapshots at redshifts spanning \(z = 0–10.2\). In our post-processing procedure, we first calculate the RT of ionizing photons (\(\lambda \leq 912\) Å) and estimate the ionization fraction of the ISM. The resulting ionization structure is then used to run the Ly\(\alpha\) RT to derive the emissivity, followed by the calculation of non-ionizing continuum photons (\(\lambda > 912\) Å) in each cell. Our fiducial run is done with \(N_{\text{ph}} = 10^5\) photon packets for each ionizing, Ly\(\alpha\), and non-ionizing components. Because the spatial resolution of the cosmological simulation is not adequate to resolve the multiple phase of the ISM, we assume a single-phase medium in each density grid. The highest refinement of the grid corresponds to a cell size comparable to the spatial resolution of 250 pc in comoving coordinate of the hydrodynamic simulation.

4. RESULTS

4.1. The Formation History of The Milky Way

Figure 1 shows the evolution of the MW galaxy from redshift \(z = 10\) to \(z = 0\) from the cosmological simulation. The gas follows the distribution of dark matter in filamentary structures, and stars form in high-density regions along the filaments. The most massive galaxy resides in the intersection of the filaments, the highest density peak in the simulated volume where gas concentrates in the deep potential well. The MW galaxy is formed by gas accretion and merger of subhalos; it has the last major merger at redshift \(z \approx 2\) (Q. Zhu et al. 2012, in preparation).

Stars start to form at \(z \approx 15\) by accretion of cold gas. As shown in Figure 2, the SFR of the main progenitor reaches \(\sim 10 M_\odot\) yr\(^{-1}\) at \(z \approx 10\), and it peaks at \(\sim 58 M_\odot\) yr\(^{-1}\) at \(z \approx 5.2\), owing to merger of gas-rich protogalaxies. Galaxy interaction induces gravitational torques and shocks, which trigger global starburst. After that, the SFR generally decreases except for a boosted bump at \(z \approx 2\) when the last major merger takes place.

Shown also in Figure 2 are the SFRs of the top 60 progenitors at different redshifts. The median and total value of these SFRs gradually increase until it reaches the peak at \(z \approx 3.5\), after which it decreases rapidly by over an order of magnitude. This evolution is in broad agreement with the observed cosmic star formation history (Hopkins & Beacom 2006), although the simulation box is somewhat small to discuss such a statistical property. The star formation at high redshifts (\(z \gtrsim 4\)) is largely fueled by inflow of cold gas and mergers of gas-rich halos, while the rapid decline of SFR at \(z \lesssim 2\) is mainly caused by feedback from stars and AGNs, and the depletion of cold gas.

The main progenitor has a total mass of \(\sim 2.6 \times 10^{10} M_\odot\) and a stellar mass of \(\sim 8.5 \times 10^{8} M_\odot\) at \(z \approx 10\). It evolved into a disk galaxy at \(z = 0\) with a total mass of \(1.6 \times 10^{12} M_\odot\) and stellar mass of \(\sim 10^{11} M_\odot\), as observed in the MW galaxy.

4.2. Ly\(\alpha\) Surface Brightness

Figure 3 shows the Ly\(\alpha\) surface brightness of the MW galaxy at different redshifts, contrasted with distributions of gas and stars of the galaxy. To facilitate comparison with observations, we adopt an intensity threshold, \(S_{\text{Ly}\alpha} = 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}\), from a recent survey of extended Ly\(\alpha\) sources at \(z \sim 3\) by Matsuda et al. (2011) to show the contours. The Ly\(\alpha\) distribution appears to trace that of the gas. At \(z \gtrsim 7.2\), the galaxy is small and compact, and the Ly\(\alpha\) emission is confined in the central high-density region. As the galaxy grows in mass and size, the Ly\(\alpha\) emission becomes more extended. At \(z = 4.2–3.1\), the gas structure is irregular due to infall along with filament of the main halo. At \(z \sim 0.0\), the galaxy shows a disk geometry with spiral structures. Indeed, the Ly\(\alpha\) map shows filamentary structures at high redshift, and spirals at \(z \sim 0.0\). We note that some of the extended Ly\(\alpha\) sources in the recent observations by Matsuda et al. (2011), which are called Ly\(\alpha\) blobs, show filamentary structures. Our galaxy at \(z = 3.1\) has...
a Ly\(\alpha\) distribution of \(\sim 50\) kpc with a surface brightness above the observational threshold. However, the size is smaller than the observed giant Ly\(\alpha\) blobs of \(\gtrsim 100\) kpc. Such large blobs are probably produced by systems of \(M_{\text{halo}} \gtrsim 10^{12} M_\odot\), more massive than our model. In addition, it was suggested that extended Ly\(\alpha\) sources of \(\gtrsim 40\) kpc become rare at \(z < 1\) (Keel et al. 2009). Recent UV surveys detected Ly\(\alpha\) from local star-forming galaxies at \(z \lesssim 1\), which showed \(\sim 10\) kpc Ly\(\alpha\) distribution above the threshold of \(S_{\text{Ly}\alpha} \sim 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\) (Hayes et al. 2007; Östlin et al. 2009). With such a detection sensitivity, our model galaxies at \(z \lesssim 1\) show the size of \(\lesssim 20\) kpc, in broad agreement with observations.

To examine the difference in distribution between stars and Ly\(\alpha\) emission more quantitatively, Figure 4 shows the surface brightness of UV continuum, which traces young stars, and Ly\(\alpha\) as a function of the distance from galaxy center at different time. At high redshift (\(z \gtrsim 5\)), the Ly\(\alpha\) distributes more extendedly than the stars, as the UV continuum decreases steeply around the virial radius, but at \(z < 3\), both emissions appear to have similar radial distribution. Such a transition is mainly due to the difference in Ly\(\alpha\) production at different epochs. The Ly\(\alpha\) emission is dominated by collisional excitation, which depends strongly on the gas density, at \(z \gtrsim 5\). At a later time, Ly\(\alpha\) from recombination of ionized gas by stellar radiation becomes more important, so Ly\(\alpha\) emission follows that of stars.

It was shown by Cowie et al. (2011) that nearby LAEs (\(z \lesssim 1.0\)) have a variety of morphologies, some are disky, while others are mostly compact galaxies. Galaxy morphology is closely tied to galaxy formation and evolution, and it is related to the galaxy mass. As demonstrated in Figure 5, which shows a sample of four galaxies of different masses at \(z = 0.2\), the Ly\(\alpha\) morphology changes with galaxy mass. In galaxies with lower mass (\(M_{\text{tot}} \lesssim 10^{11} M_\odot\)), the Ly\(\alpha\) luminosity is low (\(L_{\text{Ly}\alpha} \lesssim 10^{42} \text{ erg s}^{-1}\)), the Ly\(\alpha\) morphology is highly compact. At higher mass (\(M_{\text{tot}} \gtrsim 10^{11} M_\odot\)), the Ly\(\alpha\) luminosity is high (\(L_{\text{Ly}\alpha} \gtrsim 10^{42} \text{ erg s}^{-1}\)), Ly\(\alpha\) morphology shows disky and spiral
structures. This plot suggests that the various morphologies observed in low-redshift LAEs may reflect a wide range of galaxy mass in the sample.

We note that in Figure 4, the azimuthally averaged surface brightness at $z \gtrsim 3$ is somewhat fainter than the detection threshold of recent narrowband surveys, $\sim 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (Ouchi et al. 2008). However, since the local Ly$\alpha$ distribution is inhomogeneous and anisotropic, as shown in Figure 3, bright regions with flux above the threshold may be detectable by such surveys.

The detectability of these galaxies depends strongly on the sensitivity of the surveys. In the present work, unless noted otherwise, the Ly$\alpha$ luminosity is computed by collecting all escaped photons without a flux limit. If a detection limit of a given instrument is imposed, the luminosity of individual galaxies, in particular that of the faint ones, may be reduced significantly, as suggested by Zheng et al. (2010).

4.3. Evolution of Spectral Energy Distribution

The corresponding multi-wavelength SEDs of the galaxy sample in Figure 3 are shown in Figure 6. The shape of the SED changes significantly from $z = 10.2$ to $z = 0$, as a result of changes in radiation source and environment, since the radiation from stars, absorption of ionizing photons by gas and dust, and re-emission by the dust evolve dynamically with time. The Ly$\alpha$ line appears to be strong in all cases. The deep decline of Lyman continuum ($\lambda \lesssim 912$ Å) at high redshifts ($z \gtrsim 7$) is caused by strong absorption of ionizing photons by the dense gas. Galaxies at lower redshift have a higher floor of continuum emission from stars and accreting black holes, a higher ionization fraction of the gas, and a higher infrared bump owing to increasing amount of dust and absorption. Moreover, due to the effect of negative $k$-correction, the flux at observed frame $\lambda \gtrsim 500$ μm stays close in different redshifts.
Our calculations show that the main progenitor has a flux of \( f_\text{esc} = 0.057 \text{ mJy} \) at \( z \sim 6 \) and 0.02 \text{ mJy} at \( z \sim 8.5 \) at 850 \( \mu \text{m} \) in observed frame. The new radio telescope, Atacama Large Millimeter/submillimeter Array, may be able to detect such galaxies at \( z \sim 6 \) with \( \sim 2 \) hr integration, and at \( z \sim 8.5 \) for \( \sim 20 \) hr with 16 antennas (Yajima et al. 2011).

4.4. The Ly\( \alpha \) Properties

The resulting Ly\( \alpha \) properties of the 60 most massive progenitors from selected snapshots, and their evolution with redshift are shown in Figure 7. The top panel shows the emergent Ly\( \alpha \) luminosity \( L_{\text{Ly}\alpha} \). The main progenitor has a luminosity of \( L_{\text{Ly}\alpha} \sim 10^{43} \text{ erg s}^{-1} \) at \( z \lesssim 2 \), then increases to \( L_{\text{Ly}\alpha} \sim 10^{45} \text{ erg s}^{-1} \) at \( z = 2 - 6 \), owing to the increase of SFR. At high redshift \( z \gtrsim 6 \), the \( L_{\text{Ly}\alpha} \) decreases to \( \sim 10^{42} \text{ erg s}^{-1} \) due to low escape fraction and absorption by dust. At high redshift, the galaxy size is small and most of the stars form around the galaxy center. Hence, the dust compactly distributes around young stars, which effectively absorbs the ionizing photons. As a result, the intrinsic Ly\( \alpha \) emissivity drops even though the SFR is enhanced by the accretion of cold gas. However, most of other model galaxies show that the escape fraction of Ly\( \alpha \) and UV continuum photons monotonically increases with redshift because of lower dust content. The escaping process of continuum photons will be discussed in detail in a forthcoming paper (H. Yajima et al. 2012, in preparation).

Most of the galaxies at \( z \gtrsim 3 \) in this simulation have a luminosity below \( 10^{42} \text{ erg s}^{-1} \), the lower limit of many current observations using narrowband filters, so they may not be observable. However, the improved sensitivity of the deep survey of Cassata et al. (2011) reaches \( L_{\text{Ly}\alpha} \sim 10^{41} \text{ erg s}^{-1} \) at \( z \sim 2-6.6 \), which may detect more faint galaxies than the ones in our sample. As mentioned in previous sections, the luminosity is calculated as the sum of all escaped photons. If we consider only pixels brighter than \( S = 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \), the detection threshold of high-redshift LAE surveys (e.g., Ouchi et al. 2008, 2010), the total flux of the main progenitor is reduced by a factor of a few, resulting in \( L_{\text{Ly}\alpha} \sim 1 - 2 \times 10^{42} \text{ erg s}^{-1} \) in redshift \( z \sim 2 - 6 \), which is close to the observed \( L_{\text{Ly}\alpha} \) of LAEs in this redshift span (e.g., Gawiser et al. 2007; Gronwall et al. 2007; Ouchi et al. 2008; Ciardullo et al. 2012). This main progenitor has a halo mass of \( \sim 10^{11} \text{ M}_\odot \) at \( z \sim 6 \), and \( \sim 10^{12} \text{ M}_\odot \) at \( z \sim 2 \), in good agreement with suggestions from clustering analysis by Ouchi et al. (2010). These results suggest that some of the observed LAEs at \( z \sim 2-6 \) may be similar to the main progenitors of MW-like \( L^* \) galaxies at high redshifts.

The calculated escape fractions of Ly\( \alpha \) photons (\( f_{\text{esc}} \)) are shown in the middle panel of Figure 7. Here, the \( f_{\text{esc}} \) is estimated by correcting all escaped photons over whole solid angle and dividing by intrinsically emitted photon number. Unlike the SFR, the \( f_{\text{esc}} \) has higher values at lower redshift \( z \lesssim 2 \), then decreases gradually to \( \sim 20\% \). At \( z \gtrsim 4 \), the \( f_{\text{esc}} \) increases again. The \( f_{\text{esc}} \) of the main progenitor fluctuates in the range of \( \sim 20\% - 60\% \). The median \( f_{\text{esc}} \) at \( 2 \lesssim z \lesssim 4 \) is \( \sim 30\% \), which is consistent with the recent observation by the HETDEX Pilot Survey (Blanc et al. 2011). At lower redshift \( z \lesssim 1 \), there is a large dispersion in \( f_{\text{esc}} \), similar to the recent observation by Atek et al. (2009). This large scattering may be caused by the variation in a number of physical properties such as SFR, metallicity, and disk orientation. We will discuss the dependence of \( f_{\text{esc}} \) on these properties in detail in Section 5.1.

We note that the Ly\( \alpha \) RT calculations in our work, which take into account local ionization structure and inhomogeneous density distribution of gas and dust, produce a smaller escape fraction (\( f_{\text{esc}} \sim 20\% - 80\% \) at \( z \sim 6 \)) than that in previous semi-analytical work of Salvadori et al. (2010; \( f_{\text{esc}} \gtrsim 80\% \)) and Dayal & Libeskind (2012; \( f_{\text{esc}} \sim 60\% - 90\% \)), in which a uniform slab model was assumed. We find that more than half of Ly\( \alpha \) photons can be absorbed because dense gas and dust around the star-forming and Ly\( \alpha \)-emitting regions absorb the photons effectively.

The EW of Ly\( \alpha \) line is defined by the ratio between the Ly\( \alpha \) flux and the UV flux density \( f_{\text{UV}} \) in the rest frame, where the mean flux density of \( \lambda = 1300-1600 \text{ Å} \) in the rest frame is used. The resulting Ly\( \alpha \) EWs are shown in the bottom panel of Figure 7. Most of the galaxies have EW \( \gtrsim 20 \text{ Å} \); they are therefore classified as LAEs (e.g., Gronwall et al. 2007). The median EW increases with redshift, from \( \sim 30 \text{ Å} \) at redshift \( z = 0 \) to \( \sim 820 \text{ Å} \) at \( z = 8.5 \). This trend is in broad agreement with observations that galaxies at higher redshifts appear to have higher EW than their counterparts at lower redshifts (e.g., Gronwall et al. 2007; Ouchi et al. 2008). The high EW at \( z \gtrsim 6 \) is produced by excitation cooling, which enhances the Ly\( \alpha \) emission at high redshift, but at low redshift it reduces the EW as the stellar population ages (e.g., Finkelstein et al. 2009). Recent observations of LAEs at \( z \sim 0.2 - 0.4 \) shows that most local LAEs, unlike those at \( z \gtrsim 3 \), have EWs less than 100 Å (Deharveng et al. 2008; Cowie et al. 2011), consistent with the trend seen in our model.

We should point out that the results presented in Figure 7 are “unfiltered” by detection limit, and that we caution against taking these numbers too literally when compared with a particular survey, because the observed properties depend strongly on the
Figure 5. Relation between Lyα morphology and galaxy mass, exemplified by a sample of four galaxies at $z = 0.2$ with different masses, $M_{\text{gal}} = 4.2 \times 10^{9}, 1.7 \times 10^{10}, 1.2 \times 10^{11},$ and $1.6 \times 10^{11} \, M_{\odot}$, respectively. The left and middle columns show the distribution of gas (in green) and stars (in blue) from the cosmological simulation, respectively. The right column shows the Lyα surface brightness of the corresponding galaxies, with resulting luminosity $L_{\text{Ly} \alpha} = 2.6 \times 10^{40}, 9.8 \times 10^{40}, 1.8 \times 10^{42},$ and $9.8 \times 10^{41} \, \text{erg s}^{-1}$, respectively. The box size is 250 kpc in physical scale. Note the Lyα luminosity is computed by collecting all escaped photons. (A color version of this figure is available in the online journal.)

observational threshold. Note also in the current work, we did not include the transmission in intergalactic medium (IGM). The Lyα properties can be changed by IGM extinction. The neutral hydrogen in IGM at high redshift can scatter a part of Lyα photons, and decrease the $L_{\text{Ly} \alpha}$ and EW. For example, Laursen et al. (2011) suggested that the IGM transmission could be $\sim 20\%$ at $z = 6.5$. The transmission depends sensitively on the viewing angle and the environments of a galaxy, as it is affected by the inhomogeneous filamentary structure of IGM.

4.5. The Lyα Line Profiles

The emergent Lyα emission line of the main progenitor is shown in Figure 8. The frequency of the intrinsic Lyα photon is sampled from a Maxwellian distribution with the gas temperature at the emission location in the rest frame of the gas. Our sample Lyα lines show mostly single-peak, common profiles of LAEs observed both at high redshift ($z \sim 6$; e.g., Ouchi et al. 2010) and in the nearby universe (e.g., Cowie et al. 2010).

In a static and optically thick medium, the Lyα profile can be double peaked, but when the effective optical depth is low due to high relative gas speed or ionization state, there might be only a single peak (Zheng & Miralda-Escudé 2002). In our case, the flow speed of gas is up to $\sim 300 \, \text{km s}^{-1}$, and the gas is highly ionized by stellar and AGN radiation, which result in a single peak.

In the case at high redshift $z \gtrsim 6$, the gas is highly concentrated around the galaxy center, hence they become optically thick and cause the Lyα photons to move to the wing sides. In addition, the profile at $z = 10.2$ shifts to shorter wavelength, and it shows the characteristic shape of gas inflow (Zheng & Miralda-Escudé 2002). Although our simulation includes feedback of stellar wind similar to that of Springel et al. (2005b), the Lyα line profile indicates gas inflow in the galaxy. Our result suggests that high-redshift star-forming galaxies may
be fueled by efficient inflow of cold gas from the filaments. We will study this phenomenon in detail in H. Yajima et al. (2012, in preparation). On the other hand, it was suggested that the asymmetrically shifted profile to the red wing in some LAEs can be made by outflowing gas distribution (e.g., Mas-Hesse et al. 2003). The growing hot bubble gas around star-forming region from supernovae or radiative feedback can cause outflowing, neutral gas shells, which result in redshifted line profiles.

Recently, Yamada et al. (2012) observed a sample of 91 LAEs at $z = 3.1$, about half of which show double peaks of strong blue and weak red features thought to be caused by gas outflow, while others show a symmetric single peak in which the flux ratio of blue wing to red one is about unity. While our model may explain the latter, the missing outflow features in our line sample is probably due to the limitations of our current simulations, e.g., insufficient spatial resolution and simplified treatment of supernovae feedback.

In addition, the line profiles of galaxies at high redshift $z \gtrsim 6$ may be highly suppressed and changed by scattering in IGM (e.g., Santos 2004; Dijkstra et al. 2007; Zheng et al. 2010; Laursen et al. 2011) because the Lyα transmission through IGM is very low at the line center and at shorter wavelengths by the Hubble flow (e.g., Laursen et al. 2011). Even at lower redshift $z \sim 3$, the optical depth of IGM can be high depending on the viewing angle and the location of the galaxy (e.g., Laursen et al. 2011). Therefore, the Lyα flux with inflow featured in our model galaxies may be suppressed and the shape may change to a single peak with only the red wing, or a double peak with strong-red and weak-blue as in Figure 7 of Laursen et al. (2011).

5. DISCUSSION

5.1. Dependence of Lyα Properties on Galaxy Properties

As shown in previous sections, the Lyα properties vary significantly in different galaxies. Here we explore the dependence on a number of physical properties of a galaxy. Figure 9 shows the dependence of escape fraction $f_{\text{esc}}$ (top panels) and Lyα luminosity $L_{\text{Ly} \alpha}$ (bottom panels) on the galaxy mass, SFR, and metallicity $Z$. We apply a least-absolute-deviation fitting to the data using a power-law function, $\log Y = \alpha \log X + \beta$. 

![Figure 6](image-url)  
**Figure 6.** SEDs of the most massive galaxy in each snapshot. Only the galaxy at $z = 0.0$ is artificially set at $z = 0.1$, i.e., the flux is estimated by using the luminosity distance of $z = 0.1$. (A color version of this figure is available in the online journal.)

![Figure 7](image-url)  
**Figure 7.** Evolution of the Lyα properties of the 60 most massive progenitors from selected redshifts. From top to bottom panel is the emergent unfiltered Lyα luminosity (computed by collecting all escaped photons), escape fraction of Lyα photons over whole solid angle, and equivalent width in rest frame, respectively. The red filled circle represents the value of the main progenitor at each redshift, while the blue filled circles indicate the median value of the sample galaxies. (A color version of this figure is available in the online journal.)

![Figure 8](image-url)  
**Figure 8.** Lyα line profile of the main progenitor at different redshifts. The dotted and solid lines are the intrinsic and the emergent Lyα profile, respectively.
The mass dependence of $f_{\text{esc}}$ has a large dispersion, but from our fitting, $a \sim -0.02$ and $\beta \sim -0.17$, which suggests that $f_{\text{esc}}$ roughly decreases with the total mass, consistent with the results of Laursen et al. (2009). At $M \sim 10^{10.11} M_\odot$, the $f_{\text{esc}}$ is mostly constant at $\sim 10\%$–$30\%$. In contrast, $f_{\text{esc}}$ is more tightly correlated with the SFR, with $a \sim -0.08$ and $\beta \sim -0.41$. At high SFR, dust can be enriched quickly by Type II supernovae, and can effectively absorb the Ly$\alpha$ photons. In addition, galaxies with high SFR have more hydrogen gas. The gas decreases the dust optical depth, which reduces the escape fraction. In addition, the $f_{\text{esc}}$ decreases with metallicity, $a \sim -0.35$ and $\beta \sim -0.65$. Since the dust content linearly increases with metallicity in our model, the Ly$\alpha$ photons can be absorbed effectively by gas with high metallicity. This trend is consistent with observational indications by Atek et al. (2009) and Hayes et al. (2010).

On the other hand, the luminosity $L_{\text{Ly}\alpha}$ has different relationships with these properties from the $f_{\text{esc}}$. The $L_{\text{Ly}\alpha}$ is also roughly correlated with the mass, $L_{\text{Ly}\alpha} \approx 10^{37.7} \times M_\odot^{0.38}$, with a large dispersion. Only massive galaxies with $M_\text{tot} \gtrsim 10^{11} M_\odot$ have the Ly$\alpha$ luminosity of $L_{\text{Ly}\alpha} \gtrsim 10^{42} \text{ erg s}^{-1}$. This is consistent with suggestions from clustering analysis of observed LAEs at $z = 2$–$3$ (e.g., Gawiser et al. 2007; Guaita et al. 2010). In our model, the massive galaxies at $z = 2$–$3$ evolve into $L^*$ galaxies at $z = 0$. Hence, our results support the suggestion by Gawiser et al. (2007) that the observed LAEs with $L_{\text{Ly}\alpha} \gtrsim 10^{42} \text{ erg s}^{-1}$ at $z = 2$–$3$ are likely progenitors of local $L^*$ galaxies.

The $L_{\text{Ly}\alpha}$ has the tightest correlation with SFR among the properties investigated here: $L_{\text{Ly}\alpha} \approx 10^{41.7} \times \text{SFR}^{0.53}$. In the literature, a simple linear relation is commonly used, with $L_{\text{Ly}\alpha} \approx 1.1 \times 10^{42} \times \text{SFR} (M_\odot \text{ yr}^{-1})$, assuming that $L_{\text{Ly}\alpha}/L_{\text{H}\beta} = 8.7$ (case B). However, our result suggests that the relation between $L_{\text{Ly}\alpha}$ and SFR becomes somewhat shallower due to the dependence of $f_{\text{esc}}$ on SFR. Finally, the emergent $L_{\text{Ly}\alpha}$ does not show a strong dependence on metallicity, $L_{\text{Ly}\alpha} \approx 10^{41.1} \times (Z/Z_\odot)^{-0.27}$. This is due to the fact that although the intrinsic $L_{\text{Ly}\alpha}$ increases with halo mass (so does SFR and metallicity), the $f_{\text{esc}}$ decreases with metallicity, so $L_{\text{Ly}\alpha}$ of higher-metallicity galaxies is suppressed by dust absorption.

We should point out that the large scatter in the correlations in Figure 9 may be due to the small volume of our simulation and the small number of our galaxy sample. In addition, as we discuss in Section 5.6, a number of limitations of our model, such as the simplified ISM model and insufficient resolutions, may contribute to uncertainty in these relations. Moreover, the luminosity scaling relations may change under some specific detection limits. We will study these relations in detail with improved model and simulations in future work.

### 5.2. Redshift Dependence of LAE Fraction

The number fraction of LAEs ($f_{\text{LAE}}$) in our sample is shown in Figure 10. The detection limit of Ly$\alpha$ varies in different surveys. At high redshifts $(z \gtrsim 3)$, the LAE detection in most observations has been confined to $L_{\text{Ly}\alpha} \gtrsim 10^{42} \text{ erg s}^{-1}$. Here, we derive the $f_{\text{LAE}}$ with three $L_{\text{Ly}\alpha}$ thresholds, $L_{\text{Ly}\alpha} \gtrsim 10^{40}, 10^{41}, 10^{42} \text{ erg s}^{-1}$ with EW of $\gtrsim 20 \text{ Å}$. The $f_{\text{LAE}}$ with $L_{\text{Ly}\alpha} \gtrsim 10^{40}, 10^{41} \text{ erg s}^{-1}$ rapidly increases from $z = 0$ to $\sim 5$, and then remains nearly constant with higher values at $z \gtrsim 5$. The trend is roughly similar to the SFR history (Figure 2). Since the $L_{\text{Ly}\alpha}$ is tightly correlated with the SFR (Figure 9), the number of galaxies with $L_{\text{Ly}\alpha} \gtrsim 10^{40}, 10^{41}$ increases at $z \sim 0$–$4$. On the other hand, although the SFR decreases at $z \gtrsim 4$, the $f_{\text{esc}}$ increases due to low metallicity. Hence, the $f_{\text{LAE}}$ does not decrease at $z \gtrsim 4$.

Meanwhile, the $f_{\text{LAE}}$ with $L_{\text{Ly}\alpha} \gtrsim 10^{42} \text{ erg s}^{-1}$ is nearly constant and shows $\sim 2\%$–$10\%$. Since the SFR tightly correlates with $L_{\text{Ly}\alpha}$, and it roughly increases with the galaxy mass, some massive galaxies can be LAEs with $L_{\text{Ly}\alpha} \gtrsim 10^{42} \text{ erg s}^{-1}$. In addition, the $f_{\text{LAE}}$ of LAEs having intrinsic $L_{\text{Ly}\alpha} \gtrsim 10^{42} \text{ erg s}^{-1}$ change with cosmic star formation history. However, the $f_{\text{esc}}$ decreases around the phase of SFR peak, and therefore suppresses the $f_{\text{LAE}}$.

On the other hand, at lower redshift, the observations indicate that number density of LAEs decreases by some factors (e.g., Cowie et al. 2010). The discrepancy may come from the difference in density field and the small box in our simulation.
initial condition is a somewhat special one focused on a MW-size galaxy, and the zoom-in simulation region is \(5^3 h^{-3}\) \(\text{Mpc}^3\). Therefore, our simulation cannot reproduce the global statistics in observations. Moreover, the LAE fraction having EW > 25 Å in this work shows \(\sim 44\%\) at \(z = 4\) and \(\sim 100\%\) at \(z = 6\), which is somewhat higher than the LAE fraction in the Lyman break galaxy (LBG) sample (Stark et al. 2010, 2011; Pentericci et al. 2011; Schenker et al. 2012; Ono et al. 2012). However, in observation, the LAE fraction increases with decreasing UV brightness. Most of our model galaxies at \(z \gtrsim 3\) are fainter than the detection threshold in the LBG observation. Since the number of galaxies brighter than the threshold of LBG observation is quite small (less than 10), we need a larger sample covering a wide mass range to verify the model of LAEs. In addition, although some LAEs have been observed with UV continuum, and hence categorized as LBGs, it is inadequate to study LAEs from LBG-only sample, because a large fraction of LAEs may have UV continuum under the detection limit of current observations. We will address the general properties such as luminosity function, EW distribution and clustering systematically by using a set of uniform simulations with mean density field in larger volumes in future work.

5.3. The Viewing-angle Scatter of Escaping Ly\(\alpha\) Photons

Despite their high metallicity, a fraction of galaxies at low redshift \(z \lesssim 1\) show high escape fraction \(f_{\text{esc}}\) of Ly\(\alpha\) photons (Figure 9). We find that the escaping angle of the Ly\(\alpha\) photons depends strongly on the galaxy morphology and orientation, a phenomenon we dub as the “viewing-angle scatter.” Disky objects seen edge on can be a hundred times fainter than the same objects seen face on. In a galaxy that has a gas disk, the Ly\(\alpha\) photons escape in a preferred direction normal to the disk, but there is no clear escaping direction in compact or irregular galaxies without a gas disk. We demonstrate this effect in Figure 11. We first estimate the normal direction to the gas disk according to the total angular momentum of the gas, and set \(\theta = 0^\circ\) along this direction. In a galaxy with irregular morphology such as the main progenitor at \(z = 3.1\), there is no clear preferred escaping angle, as illustrated in the top panel of Figure 11. However, in a spiral galaxy with rotationally supported gas disk such as the MW galaxy at \(z = 0\) in our simulation, the escaping angle is strongly confined to \(\cos \theta \simeq \pm 1\), corresponding to \(\theta \simeq 0^\circ\) or \(180^\circ\), as shown in the bottom panel of Figure 11. This is due to the fact that the Ly\(\alpha\) photons have the minimum optical depth along the normal direction to the gas disk. More than 60% of the Ly\(\alpha\) photons escapes in the direction of \(|\cos \theta| \lesssim 0.5\). Generally, the Ly\(\alpha\) flux from our model galaxies can scatter around the mean value typically by a factor of 10 just from different orientations.

As illustrated in Figure 3, most galaxies in our simulation have highly irregular shapes at high redshift due to accretion and gravitational interaction. At \(z = 0\), a number of them evolve into spiral disks. The “viewing-angle scatter” explains why we see high Ly\(\alpha\) escape fractions in a number of low-z galaxies, and the fact that Ly\(\alpha\) is detected in a large number of face-on spiral galaxies in the nearby universe (e.g., Cowie et al. 2010).

5.4. Contribution of Excitation Ly\(\alpha\) Cooling

There are two major mechanisms to generate Ly\(\alpha\) emission, the recombination of ionizing photons and the collisional excitation of hydrogen gas. However, the relative contribution between the two mechanisms is not well understood. From our calculations, we find that the contributing fraction of excitation Ly\(\alpha\) emission to the total intrinsic Ly\(\alpha\) luminosity increases with redshift, as shown in Figure 12.

In our cosmological simulation, galaxy evolution is accompanied by cold, filamentary gas streams with temperature \(T \sim 10^4–10^5\) K, which penetrate deep inside dark matter.
halos (Q. Zhu et al. 2012, in preparation; H. Yajima et al. 2012, in preparation), a phenomenon also reported by other groups (Katz et al. 2003; Kereš et al. 2005, 2009; Birnboim & Dekel 2003; Dekel & Birnboim 2006; Ocvirk et al. 2008; Brooks et al. 2009; Dekel et al. 2009). Such cold gas can efficiently produce the excitation Lyα cooling photons (Dijkstra & Loeb 2009; Faucher-Giguère et al. 2009; Goerdt et al. 2010). At higher redshift, galaxies form through more efficient gas accretion and more frequent merging event. As a result, the contributing fraction increases with redshift and becomes dominant at $z \gtrsim 6$. This excitation mechanism does not depend on the stellar radiation, and can therefore produce high Lyα EWs. We find that the EWs of LAEs increases significantly at $z \gtrsim 6$, reaching $\gtrsim 10^3 \, \text{Å}$ at $z \sim 10$. This is larger than the upper limit of EW, 240 Å, which considers only stellar sources assuming a Salpeter IMF with solar abundance of metallicity (Charlot & Fall 1993). Although the upper limit increases with decreasing metallicity, it was suggested that top-heavy IMF like Population III stars are needed for making EW $> 400 \, \text{Å}$ (Schaerer 2003; Raiter et al. 2010). However, even though Salpeter IMF is used in this work and the stellar metallicity is mostly $Z/Z_{\odot} \gtrsim 10^{-3}$, we find that the EW can be higher than the upper limit by the efficient excitation Lyα emission. On the other hand, the Lyα line is strongly damped by IGM correction at $z \gtrsim 6$ (Haiman 2002; Laursen et al. 2011; Dayal & Libeskind 2012), which can result in a lower EW. The suppression by IGM highly depends on the inhomogeneous ionization structure around LAEs (e.g., McQuinn et al. 2007; Mesinger & Furlanetto 2008; Iliev et al. 2008). We will address the detectability of high-redshift LAEs and EW after IGM correction by running large-scale Lyα RT in IGM in future work.

5.5. Lyα Luminosity Functions

The simulation box in this work is too small to study global statistics directly. As a rough estimate, the luminosity–halo-mass correlation we find above may be used to construct Lyα LFs at different redshift when combined with halo mass functions from large-box, general cosmological simulations. For example, at $z = 3.1$, we divide all galaxies in the snapshot by the halo mass with 0.25 dex, and fit to the median value of each bin, this gives a correlation of $L_{\text{Lyα}} \, (\text{erg s}^{-1}) = 10^{32.94} \times (M_{\text{halo}} / M_{\odot})$. We then use this to convert the halo mass function of Sheth & Tormen (1999) to the Lyα LF.

Figure 13 shows the resulting Lyα LFs in comparison with observations at redshift $z = 3.1, 5.7$, respectively. The red solid curves are LFs above a detection threshold of $S_{\text{Lyα}} = 10^{-18} \, \text{erg s}^{-1} \, \text{cm}^{-2} \, \text{arcsec}^{-2}$ (Ouchi et al. 2008, 2010), while the red dashed lines represent LFs from total luminosity (counting all escaped photons without a flux cut).

While the unfiltered LFs seem to agree with observations of Gronwall et al. (2007) and Ouchi et al. (2008), the filtered ones are significantly off. The difference comes from the reduction of $L_{\text{Lyα}}$ and $f_{\text{esc}}$ due to the flux cut. Moreover, the dispersion in the luminosity–halo-mass relation at different redshift may cause a large scatter in the LFs. This plot suggests that the current simulation in this work is not suitable to study a large galaxy population and its statistical properties because there are too few observable LAEs. Moreover, as discussed earlier, the predicted Lyα properties may be affected by a number of numerical and physical limitations of our model. For example, the one-phase model currently used in the present work may underestimates the density of cold hydrogen gas, and hence underestimates the Lyα flux. We will study the Lyα LFs at different redshift in a forthcoming paper with the improved ART2 which incorporates a two-phase ISM model, and a general simulation with mean overdensity in a larger volume (H. Yajima et al. 2012, in preparation).

5.6. Limitations of Our Model

As demonstrated above, our model is able to explain a number of observed properties of LAEs at different redshift. However, we should point out that our current simulations suffer from a number of major limitations which may affect the predicted Lyα properties.

1. In the current work, we use a one-phase ISM model, which considers the average density and temperature of the gas. Such a model likely underestimates the density of cold hydrogen gas, which may lead to a significant underestimate of the Lyα emission coming from cold ($\sim 10^4 \, \text{K}$), dense gas. On the other hand, such a model also underestimates the amount of dust associated with cold molecular gas, which likely results in an underestimate of absorption of Lyα photons by gas and dust. We will investigate the Lyα RT and ionization structures in a two-phase ISM model in a forthcoming paper.

2. The absorption and transmission of IGM are not taken into account in the RT calculations. As discussed in the previous section, these two effects may suppress the Lyα flux and change the line profiles.

3. The simulations do not have sufficient resolutions to resolve dense regions and outflow, which requires a high spatial resolution of $\sim \text{pc}$ (e.g., Fujita et al. 2009). It is a challenge for cosmological simulations to resolve both the inflow gas from large scales of $\sim \text{Mpc}$ and the outflow from pc-scale star-forming regions. For a simulation with a box...
of 100 Mpc like the one we have, this requires a large dynamical range over eight orders of magnitude, which is beyond the scope of our current work.

4. The simulation box in this work is too small to study a large galaxy population, as well as effects of environment on galaxy properties and their evolution. One needs uniform simulations in large volumes in order to systematically investigate the formation and evolution of $L^*$ galaxies.

Finally, we stress once again that caution should be taken when comparing directly the results from our calculations to data from a given survey because, as discussed above, the observed Ly$\alpha$ properties depend sensitively on a number of factors, including galaxy properties, viewing angle, model parameters, and observational threshold.

6. SUMMARY

To summarize, we have investigated the Ly$\alpha$ properties of progenitors of a local $L^*$ galaxy by combining cosmological hydrodynamic simulations with three-dimensional radiative transfer calculations using the new ART$^3$ code. Our cosmological simulation follows the formation and evolution of a MW-size galaxy and its substructures from redshift $z = 127$ to $z = 0$. It includes important physics of dark matter, gas dynamics, star formation, black hole growth, and feedback processes, and has high spatial and mass resolutions to resolve an MW-like galaxy at $z = 0$ and its progenitors at higher redshifts. Our radiative transfer couples Ly$\alpha$ line, ionization of neutral hydrogen, and multi-wavelength continuum radiative transfer, which enables a self-consistent and accurate calculation of the Ly$\alpha$ properties in galaxies.

We find that the main progenitor of the MW galaxy is Ly$\alpha$ bright at high redshift, with the emergent Ly$\alpha$ luminosity close to the observed characteristic $L_{\text{Ly}\alpha}^*$ of LAEs at $z \sim 2$–6. Most of the fainter galaxies in the simulation fall below the detection threshold of many current surveys. The Ly$\alpha$ escape fraction correlates with a number of physical properties of the galaxy, such as mass, SFR, and metallicity. We find a “viewing-angle scatter” in which the photon escape depends strongly on the galaxy morphology and orientation, such that the Ly$\alpha$ photons escape in a preferred direction normal to the gas disk at $z \sim 0$ and its progenitors at higher redshifts. Our results suggest that galaxies at high redshift form through accretion of cold gas, which accounts for the high EWs, the blueshifted line profiles, and the dominant contribution from excitation cooling in Ly$\alpha$ emission. Moreover, some of the observed LAEs at $z \sim 2$–6 with $L_{\text{Ly}\alpha} = 10^{42}$–$10^{43}$ erg s$^{-1}$ may evolve into present-day $L^*$ galaxies such as the MW.

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REFERENCES

Acquaviva, V., Vargass, C., Gawiser, E., & Guaita, L. 2012, ApJ, 751, L26
Atek, H., Kunth, D., Schaerer, D., et al. 2009, A&A, 506, L1
Barnes, J., & Hut, P. 1986, Nature, 324, 446
Birnboim, Y., & Dekel, A. 2003, MNRAS, 345, 349
Blanc, Adams, J. J., Gebhardt, K., et al. 2011, ApJ, 736, 31
Bondi, H. 1952, MNRAS, 112, 195
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Brooks, A. M., Governato, F., Quinn, T., Brook, C. B., & Wadsley, J. 2009, ApJ, 694, 396
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Cassata, P., Le Fèvre, O., Garilli, B., et al. 2011, A&A, 525, 143
Charlot, S., & Fall, S. M. 1993, ApJ, 415, 580
Ciardullo, R., Gronwall, C., Wolf, C., et al. 2012, ApJ, 744, 110
Cowie, L. L., Barger, A. J., & Hu, E. M. 2010, ApJ, 711, 928
Cowie, L. L., Barger, A. J., & Hu, E. M. 2011, ApJ, 738, 136
Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319
Davé, R., Hernquist, L., Katz, N., & Weinberg, D. H. 1999, ApJ, 511, 521
Dayal, P., Ferrara, A., & Gallierani, S. 2008, MNRAS, 389, 1683
Dayal, P., & Libeskind, N. I. 2012, MNRAS, 419, L9
Deharveng, J.-M., Small, T., Barlow, T. A., et al. 2008, ApJ, 680, 1072
Dekel, A., & Birnboim, Y. 2006, MNRAS, 368, 2
Dekel, A., Birnboim, Y., Engel, G., et al. 2009, Nature, 457, 451
Dijkstra, M., Lidz, A., & Wyithe, J. S. B. 2007, MNRAS, 377, 1175
Dijkstra, M., & Loeb, A. 2009, MNRAS, 400, 1109
Di Matteo, T., Colberg, J., Springel, V., Hernquist, L., & Sijacki, D. 2008, ApJ, 676, 33
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Faucher-Giguère, C., Lidz, A., Zaldarriaga, M., & Hernquist, L. 2009, ApJ, 703, 1416
Finkelstein, S. L., Cohen, S. H., Malhotra, S., & Rhoads, J. E. 2009, ApJ, 700, 276
Finkelstein, S. L., Hill, G. J., Gebhardt, K., et al. 2011, ApJ, 729, 140
Fujita, A., Martin, C. L., Mac Low, M.-M., New, K. C. B., & Weaver, R. 2009, ApJ, 698, 693
Gawiser, E., Francke, H., Lai, K., et al. 2007, ApJ, 671, 278
Gawiser, E., van Dokkum, P. G., Gronwall, C., et al. 2006, ApJ, 642, L13
Goerdt, T., Dekel, A., Sternberg, A., et al. 2010, MNRAS, 407, 613
Gronwall, C., Ciardullo, R., Hickey, T., et al. 2007, ApJ, 667, 79
Guaita, L., Gawiser, E., Padilla, N., et al. 2010, ApJ, 714, 255
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Haiman, Z. 2002, ApJ, 576, L1
Hayes, M., Östlin, G., Atek, H., et al. 2007, MNRAS, 378, 1465
Hayes, M., Östlin, G., Schaerer, D., et al. 2010, Nature, 464, 562
Hayes, M., Schaerer, D., Östlin, G., et al. 2011, ApJ, 730, 8
Hernquist, L., & Katz, N. 1989, ApJS, 70, 419
Hockney, R. W., & Eastwood, J. W. (ed.) 1981, Computer Simulation Using Particles (New York: McGraw-Hill)
Hopkins, A. M., & Beacom, J. F. 2006, ApJ, 651, 142
Hopkins, P. F., Hernquist, L., Cox, T. J., et al. 2006, ApJS, 163, 1
Hoyle, F., & Lyttleton, R. A. 1941, MNRAS, 101, 227
Hu, E. M., & Cowie, L. L. 2006, Nature, 440, 1145
Hu, E. M., Cowie, L. L., Barger, A. J., et al. 2010, ApJ, 725, 394
Hu, E. M., & McMahon, R. G. 1996, Nature, 382, 231
Hui, L., & Gnedin, N. Y. 1997, MNRAS, 292, 27
Iliev, I. T., Shapiro, P. R., McDonald, P., Mellema, G., & Pen, U.-L. 2008, MNRAS, 391, 63
Iye, M., Ota, K., Kashikawa, N., et al. 2006, Nature, 443, 186
Kashikawa, N., Shimazaki, K., Malkan, M. A., et al. 2006, ApJ, 648, 7
