COLD ACCRETION IN EARLY GALAXY FORMATION AND ITS Lyα SIGNATURES

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1. INTRODUCTION

The quest for the first galaxies formed at the cosmic dawn is a major frontier in both observational and theoretical cosmology (Bromm & Yoshida 2011). Over the past few years, significant progress has been made in detecting galaxies at redshifts $z > 7$. It may also contain important information concerning the origin of these galaxies. Here, we investigate the formation of a typical $L^*$ galaxy and its observational signatures at the earliest stage by combining a cosmological hydrodynamic simulation with three-dimensional radiative transfer (RT) calculations using the newly improved ART2 code. Our cosmological simulation uses the Aquila initial condition, which zooms in on a Milky-Way-like halo with high resolutions, and our RT couples multi-wavelength continuum, Lyα line, and ionization of hydrogen. We find that the modeled galaxy starts to form at redshift $z \sim 24$ through the efficient accretion of cold gas, which produces a strong Lyα line with a luminosity of $L_{\text{Ly}\alpha} \sim 10^{42}$ erg s$^{-1}$ as early as $z \sim 14$. The Lyα emission appears to trace the cold, dense gas. The lines exhibit asymmetric, single-peak profiles, and are shifted to the blue wing, a characteristic feature of gas inflow. Moreover, the contribution to the total Lyα luminosity from excitation cooling increases with redshift and becomes dominant at $z \gtrsim 6$. We predict that $L^*$ galaxies such as the modeled one may be detected at $z \lesssim 8$ by the James Webb Space Telescope and Atacama Large Millimeter Array with a reasonable integration time. Beyond redshift 12, however, the Lyα line may only be observable by spectroscopic surveys. Our results suggest that the Lyα line is one of the most powerful tools to detect the first generation of galaxies and decipher their formation mechanism.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – line: profiles – methods: numerical – radiative transfer

In this work, we explore the physical conditions of early galaxy formation on a larger scale. In particular, we focus on the gas properties and its Lyα emission. Recent simulations have revealed that a large amount of gas penetrates deep inside dark matter halos as cold, filamentary streams (Katz et al. 2003; Birnboim & Dekel 2003; Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Ocvirk et al. 2008; Brooks et al. 2009; Dekel et al. 2009), and Dekel et al. (2009) showed that massive galaxies at $z = 2 - 3$ can actively form stars from the inflow of cold gas. More recently, Di Matteo et al. (2012) suggested that massive galaxies at $z \gtrsim 6$ can grow by cold accretion and evolve with black holes. Such streams of cold gas may produce a large number of Lyα photons via the excitation cooling and give rise to the Lyα emission detected in the early galaxies (Dijkstra & Loeb 2009; Faucher-Giguère et al. 2010; Latif et al. 2011; Yajima et al. 2012a, 2012b).

We combine a multi-scale cosmological hydrodynamic simulation with multi-wavelength radiative transfer (RT) calculations. The simulation uses the Aquila initial condition and follows the formation and evolution of a Milky-Way-size galaxy (Wadepuhl & Springel 2011; Scannapieco et al. 2012). It covers a large dynamical range from a $100 h^{-1}$ Mpc box down to a $\sim 5 h^{-3}$ Mpc zoom-in region, which is ideal for studying the gas inflow on a large scale. The RT calculations use the three-dimensional Monte Carlo RT code ART2 by Li et al. (2008) and Yajima et al. (2012a). The ART2 code couples the multi-wavelength continuum, the Lyα line, and the ionization of hydrogen, which is critical for studying the Lyα and multi-band properties of early galaxies.
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 the results, which include the Lyα properties and detectability by the upcoming missions the James Webb Space Telescope (JWST) and Atacama Large Millimeter Array (ALMA). We discuss the implications and limitations of our model in Section 4 and summarize in Section 5.

2. MODEL AND METHODOLOGY

We carry out a cosmological simulation with the Aquila initial condition which can reproduce a Milky-Way-like galaxy at $z = 0$ (Springel et al. 2008; Scannapieco et al. 2012). The whole simulation box is $100 h^{-1}$ Mpc on each side with a zoom-in region of $5 \times 5 \times 5 h^{-3}$ Mpc$^3$. The spatial resolution in the zoom-in region is $\sim 250 h^{-1}$ pc and the mass resolution is $1.8 \times 10^6 h^{-1} M_\odot$ 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 $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\sigma_8 = 0.9$, and $h = 0.73$, consistent with the five year results of WMAP (Komatsu et al. 2009). The simulation was performed using the N-body/smoothed particle hydrodynamics (SPH) code GADGET-3 (Springel et al. 2001; Springel 2005). The specifics of the simulation were described in Zhu et al. (2012) and we refer readers to that paper for more details.

In this work, we use the 3D Monte Carlo RT code All-wavelength RT with Adaptive Refinement Tree (ART2) to study the multi-wavelength properties of our model galaxies. The ART2 code includes continuum photons from X-ray to radio, the Lyα line, and the ionization structure in the adaptive refinement grids. The detailed prescriptions of the code were presented in Li et al. (2008) and Yajima et al. (2012a). The Lyα emission comes from the recombination and de-excitation process,

$$\epsilon_{\text{Ly} \alpha} = f_{\alpha} \alpha_B h \mu_n n_e n_{\text{HII}} + C_{\text{Ly} \alpha} n_e n_{\text{HII}},$$

where $\alpha_B$ is the case B recombination coefficient and $f_{\alpha}$ is the average number of Lyα photons produced per case B recombination. The $\alpha_B$ derived in Hui & Gnedin (1997) is used. Due to the small dependence of $f_{\alpha}$ on temperature, we assume $f_{\alpha} = 0.68$ everywhere (Osterbrock & Ferland 2006). $C_{\text{Ly} \alpha}$ is the collisional excitation coefficient, $C_{\text{Ly} \alpha} = 3.7 \times 10^{-17} \exp(-h \nu/kT) T^{-1/2} \ erg \ cm^3$ (Osterbrock & Ferland 2006). The Lyα emissivity and opacity highly depend on the ionization structure in the galaxies. We first calculate the ionization structure due to internal stellar sources and then simulate the Lyα RT. We cast $N_{\text{ph}} = 10^5$ photon packets for each ionizing, Lyα, and non-ionizing component, which showed good convergence (Yajima et al. 2012a, 2012b). In addition, interstellar dust is included to consider the dust extinction of Lyα and continuum photons, and to simulate the dust thermal emission (see also Yajima et al. 2012a). The intrinsic spectral energy distributions (SEDs) of stars are calculated by GALAXEV (Bruzual & Charlot 2003) with the assumption of Salpeter IMF. For the SED of AGNs, a broken power law is used (Li et al. 2008). For the intrinsic SEDs, we do not include the Lyα line as nebula emission. This is because here we calculate the RT of ionizing photons and ionization structure. Some fraction of ionizing photons are absorbed in situ and converted to Lyα photons via the recombination process. Therefore, the nebula emission at the Lyα line is included in the post-processing calculations.

3. RESULTS

In our previous work (Zhu et al. 2012), we presented the formation history of the MW Galaxy and applied ART2 to the Aquila progenitors simulation to study the multi-band properties of MW progenitors (Yajima et al. 2012a) and the escape of Lyα and continuum photons (Yajima et al. 2012b). In this paper, we focus on the earliest evolutionary stage of the MW and the Lyα properties from $z \sim 6 - 14$.

3.1. The Accretion of Cold Gas

The modeled MW Galaxy starts to form at $z \sim 24$. Figure 1 shows the distribution of the gas density, gas temperature, and stellar density of the MW main progenitor from a redshift of $z \sim 14$ to $z \sim 6$. The gas follows the distribution of dark matter and exhibits filamentary structures. At $z \geq 6$, the gas is predominantly cold with a mean temperature of $\sim 10^4 K$. Stars form from such cold gas, so they also distribute along the filaments.

The star formation at $z \geq 6$ is fueled by the efficient accretion of cold gas, as demonstrated in Figure 2. The gas accretion rate is defined as the inflow rate of gas within the virial radius of the modeled galaxy. It peaks around $10^4 K$ in all cases. At a later time, feedback from both stars and accreting BHs heats up the gas. Also, the gas can be heated by gravitational shocks during the infall. Therefore the accretion includes hot gas as well. The inflow gas falls along the filaments toward the intersection, the highest density peak where the first Galaxy in the simulated volume forms.

Figure 3 shows the star formation history of the MW. The star formation rate (SFR) increases steadily from $\sim 3 \times 10^{-3} M_\odot \ yr^{-1}$ at $z \sim 24$ to $\sim 15 M_\odot \ yr^{-1}$ at $z \sim 8.5$, and it peaks at $\sim 62 M_\odot \ yr^{-1}$ at $z = 5.2$ due to the merging processes of gas-rich galaxies. The galaxy mass increases rapidly during this cold accretion phase. By $z \sim 8.5$, it reaches a total mass of $\sim 5.6 \times 10^{10} M_\odot$ and a stellar mass of $\sim 6 \times 10^9 M_\odot$.

3.2. The Lyα Properties

The Lyα emission traces the gas distribution, as shown in Figure 4. The surface brightness rises above $10^{-20} \ erg \ cm^{-2} \ arcsec^{-2}$ at $z \lesssim 14$. At high redshift $z \gtrsim 10$, the galaxy is small, and the Lyα emission is faint and confined to the central high-density region. The Lyα emission increases with the mass and size of the Galaxy, and it becomes stronger and more extended and irregular due to mergers and gas infall along the filaments of the main halo.

Figure 5 shows the Lyα properties of the MW Galaxy from $z \sim 14$ to $z \sim 6$, including the emergent Lyα luminosity ($L_{\text{Ly} \alpha}$), equivalent width (EW) of the Lyα line in the rest frame, and the photon escape fraction of the Lyα and UV continuum (1300–1600 Å). For comparison with star formation activity, the SFR of the galaxy at the corresponding redshift is also shown.

During this early growth phase, the SFR of the galaxy increases from $\sim 1 M_\odot \ yr^{-1}$ at $z \sim 14.0$ to $\sim 31 M_\odot \ yr^{-1}$ at $z \sim 6$ due to an abundant supply of cold gas from the infall and merging of gas-rich mini halos. The resulting emergent Lyα
Figure 1. Distribution of gas density (left column), gas temperature (middle column), and stellar density (right column) of the MW Galaxy at $z \sim 14, 10.4, 8.5,$ and 6.2, respectively. The box size is 1 Mpc in comoving scale. The temperature of the gas is in Kelvin in log scale, as indicated in the color bar.
luminosity shows a similar trend, increasing from \( \sim 1.6 \times 10^{42} \text{ erg s}^{-1} \) at \( z \sim 14.0 \) to \( \sim 5.5 \times 10^{42} \text{ erg s}^{-1} \) at \( z \sim 6.0 \). If we consider only the recombination process with the assumption of \( L_{\text{Ly}\alpha}/H_{\beta} = 8.7 \) (in which the \( H_{\beta} \) is a tracer of star formation), the intrinsic \( \text{Ly}\alpha \) luminosity should be linearly proportional to SFR, \( L_{\text{Ly}\alpha} \text{ (erg s}^{-1}) = 1.1 \times 10^{42} \times \text{SFR (M}_\odot \text{ yr}^{-1}) \) (Kennicutt 1998). However, the evolution of \( L_{\text{Ly}\alpha} \) in Figure 5 differs from the SFR history. This is due to the contribution from excitation cooling to the \( \text{Ly}\alpha \) emission, as we will discuss later, and dust absorption of the \( \text{Ly}\alpha \) photons. In particular, at \( z \gtrsim 10 \), the \( L_{\text{Ly}\alpha} \) increases with redshift, in the opposite direction from the SFR, as a result of high collisional excitation and high \( f_{\text{esc}} \).

The lower left panel of Figure 5 shows the photon escape fraction of \( \text{Ly}\alpha, f_{\text{esc, Ly}\alpha} \), and the UV continuum \( f_{\text{esc, UV}} \), where \( f_{\text{esc, UV}} \) is calculated at \( \lambda_{\text{rest}} = 1300–1600 \text{ Å} \). The \( f_{\text{esc, Ly\alpha}} \) of the modeled Galaxy falls in the range of 0.49–0.81 and increases with redshift. In our model, the dust is produced by type-II supernovae (Li et al. 2008). The dust amount increases as star formation rises from \( z \sim 14 \) to \( z \sim 6 \), and hence it efficiently absorbs the \( \text{Ly}\alpha \) and UV continuum photons, resulting in a decreasing escape fraction. However, even at \( z = 8.5 \), about 40% of the \( \text{Ly}\alpha \) photons are absorbed by dust. This is due to the fact that in the early phase, galaxies are gas rich and compact, and the gas and dust are highly concentrated in the galaxies, resulting in effective absorption of the the \( \text{Ly}\alpha \) and UV photons by the dust.

The resulting \( \text{Ly}\alpha \) EW is shown in the lower-right panel of Figure 5. The EW is estimated from the \( \text{Ly}\alpha \) flux divided by the UV flux density at \( \lambda = 1300–1600 \text{ Å} \). The modeled galaxy has \( \text{EW} \gtrsim 20 \text{ Å} \) at these redshifts, and is therefore classified as an LAE (e.g., Gronwall et al. 2007). The EW increases with redshift, from \( \sim 93 \text{ Å} \) at \( z \sim 6 \) to \( \sim 2300 \text{ Å} \) at \( z \sim 14.0 \). Such a trend is similar to that reported in recent observations which showed that galaxies at higher redshift have higher EWs than their lower-redshift counterparts (e.g.,

![Figure 2](image1.png)

**Figure 2.** Gas accretion rate by the MW Galaxy as a function of gas temperature at different redshift.

![Figure 3](image2.png)

**Figure 3.** Growth history of the MW Galaxy illustrated by the star formation rate (top panel) and the accumulated mass (bottom panel), where the filled circle represents the total mass and the open circle represents the stellar mass.
Figure 4. Evolution of the Ly$\alpha$ surface brightness of the MW Galaxy with redshift at $z \sim 14, 10.4, 8.5,$ and $6.2$, respectively. The box size is 1 Mpc in the comoving scale. The color indicates the Ly$\alpha$ surface brightness in log scale in units of erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$.

Figure 5. Ly$\alpha$ properties of the modeled galaxy from $z \sim 14$ to $z \sim 6$, including, in clockwise direction, star formation rate, emergent Ly$\alpha$ luminosity, equivalent width of Ly$\alpha$ line in rest frame, and photon escape fraction of Ly$\alpha$ (filled circles) and UV continuum ($1300 - 1600$ Å, open circles). Open triangles and squares represent the modified Ly$\alpha$ properties considering the detection thresholds of the surface brightness with $10^{-18}$ and $10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, respectively.
Gronwall et al. 2007; Ouchi et al. 2008). This is because the contribution from excitation Lyα cooling becomes large with increasing redshift, as shown in Figure 6 in the next section, which boosts the EW significantly (Yajima et al. 2012a, 2012b).

The currently most distant LAE at \( z = 7.5, z_{8} \), has an \( \text{Ly}\alpha \) luminosity of \( \sim 1.8 \times 10^{42} \text{ erg s}^{-1} \) (Finkelstein et al. 2013). Our model shows a similar \( \text{Ly}\alpha \) luminosity at this redshift, and hence may be reproducing the observed LAE. However, there are additional uncertainties which may reduce the \( \text{Ly}\alpha \) flux of our calculation as we explain at the below and Section 3.4.

Next generation telescopes will have very high angular resolution, for example, that of JWST will reach \( \lesssim 0.1 \) arcsec. Some extended fainter parts, as seen in Figure 4, can be lost in observations with such a resolution. As a result, the observed \( \text{Ly}\alpha \) flux is likely to be lower than what galaxies are actually emitting. In practice, for Figure 4, if we count up only fluxes of pixels brighter than \( 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \), which is the detection threshold of recent observation of an extended \( \text{Ly}\alpha \) source with a narrow-band filter (e.g., Matsuda et al. 2012), the \( \text{Ly}\alpha \) fluxes are reduced by a factor of \( \sim 5.7 \) at \( z = 6.2 \) and \( \sim 61.0 \) at \( z = 12.1 \). Open triangles and squares in Figure 5 show the \( \text{Ly}\alpha \) properties by considering the detection thresholds of the surface brightness with \( 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \), respectively. The \( \text{Ly}\alpha \) luminosity and EW of our model galaxies can be significantly reduced in the mock observation with a threshold of \( 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \). In particular, the galaxies at \( z > 10 \) become too faint to be detected in the current observation. On the other hand, if the surface brightness threshold is \( \sim 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \), then we detect 85.9\% of the flux for \( z = 6.2 \) and 42.5\% for \( z = 12.1 \). However, the narrow-band filter imaging by F164N on JWST will require a very long exposure time \( \gtrsim 10^{4} \) hr to achieve the detection threshold for \( 5 \sigma \) detection. Therefore, although galaxies have complex \( \text{Ly}\alpha \) distributions reflecting gas and stellar distribution, most of them can be lost in observation. Due to the loss of faint extended parts, the high-\( z \) galaxies can be faint in the \( \text{Ly}\alpha \) band or undetectable with current (or future) observations, although they are intrinsically bright.

### 3.3. Contribution of Excitation Cooling to \( \text{Ly}\alpha \) Emission

As mentioned in Section 2, the \( \text{Ly}\alpha \) emission is generally produced by the recombination of ionizing photons and the collisional excitation of hydrogen gas. 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 the dark matter halos (Q. Zhu et al. 2015 in preparation; Yajima et al. 2012b), which was also shown by previous theoretical works (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). The \( \text{Ly}\alpha \) emissivity due to collisional excitation is sensitive to gas temperature and peaks in efficiency at \( T \sim 10^{4} \) K (Faucher-Giguère et al. 2009). Hence, many excitation \( \text{Ly}\alpha \) cooling photons can be emitted from such cold accreted gas (Dijkstra & Loeb 2009; Faucher-Giguère et al. 2009; Goerd et al. 2010). At higher redshifts, galaxies experience more merging events and accrete more cold gas efficiently, which results in stronger \( \text{Ly}\alpha \) emission from excitation cooling and higher \( \text{Ly}\alpha \) EWs (Yajima et al. 2012a, 2012b).

As shown in Figure 6, the fraction of intrinsic excitation cooling \( \text{Ly}\alpha \) to the total intrinsic \( \text{Ly}\alpha \) luminosity increases from \( \sim 65\% \) at \( z \sim 6 \) to \( \sim 88\% \) at \( z \sim 14 \). Such extremely high excitation \( \text{Ly}\alpha \) cooling produces the extremely high \( \text{Ly}\alpha \) EWs seen in Figure 5.

The \( \text{Ly}\alpha \) luminosity of our model, which is mainly contributed by excitation cooling, is higher than the model at \( z = 3 \) in Faucher-Giguère et al. (2010). For example, they showed \( L_{\text{Ly}\alpha} \lesssim 10^{42} \) erg s\(^{-1}\) at the halo mass \( M_{h} \sim 10^{13} M_{\odot} \). On the other hand, when our model galaxy has a similar mass at \( z = 7.2 \), it shows \( L_{\text{Ly}\alpha} = 6.6 \times 10^{46} \) erg s\(^{-1}\) without dust extinction. This may be due to the difference of the conversion efficiency from gravitational energy to \( \text{Ly}\alpha \) cooling. Faucher-Giguère et al. (2010) used 0.3 as the conversion efficiency (see also Dijkstra & Loeb 2009). In addition, recently Rosdahl & Blaizot (2012) showed that the conversion efficiency is \( \sim 0.1 - 0.2 \) by radiative-hydrodynamics simulations. However, this conversion efficiency depends sensitively on the detailed gas structure in and around galaxies (Rosdahl & Blaizot 2012). In some situations, cold-accreted gas is disturbed by interstellar gas and heated up (Rosdahl & Blaizot 2012). In our model, galaxies are compact and very dense (Yajima et al. 2014), and hence a large fraction of accreted gas might be heated due to friction with the interstellar medium. Then, since the temperature of the cold accretion gas is \( \gtrsim 10^{4} \) K, most of the thermal energy can be converted to \( \text{Ly}\alpha \) photons (Thoul & Weinberg 1996). In addition, the \( \text{Ly}\alpha \) luminosity from excitation cooling can increase with redshift because the \( \text{Ly}\alpha \) emissivity is proportional to the square of the gas density (Equation (1)) and the mean gas density of galaxies increases with redshift (e.g., Bryan & Norman 1998).

In practice, Goerd et al. (2010) showed that \( L_{\text{Ly}\alpha} = 1.88 \times 10^{42} \) erg s\(^{-1}\) \( (M_{h}/10^{12} M_{\odot})^{0.5}(1+z)^{1.3} \) by their cosmological hydrodynamics simulations with a simple dust absorption model. The \( \text{Ly}\alpha \) luminosities of our model galaxies are consistent with their estimation. Note that the \( \text{Ly}\alpha \) cooling rate balances the heating rate and is sensitive to temperature. The heating rate may not simply increase with redshift while the mean gas density does. If the gas temperature is higher than \( \sim 10^{5} \) K, the thermal energy can be released by different
cooling radiation, e.g., recombination, free–free emission (Thoul & Weinberg 1996). In addition, the Lyα luminosity by the excitation cooling in our simulations at $z = 3$, which is $L_{\text{Ly}\alpha} = 1.9 \times 10^{42} \text{ erg s}^{-1}$ at $M_\odot = 5.9 \times 10^{11} M_\odot$, is close to that in Faucher-Giguère et al. (2010). Thus, the Lyα luminosity of our model at $z > 6$ can be higher than the analytical model of Faucher-Giguère et al. (2010) at $z = 3$ by some factors.

The current code does not distinguish between excitation and recombination Lyα photons in the RT calculations. However, the fraction of the excitation Lyα cooling rate may not change significantly for mock observations with different surface brightness thresholds. This is because, as shown in Yajima et al. (2012b), Lyα photons are mostly emitted at galactic centers, and travel with many scatterings in interstellar medium, resulting in faint extended parts. Therefore, mock observation with the different thresholds of surface brightness can miss both the excitation and recombination Lyα photons at the faint parts.

### 3.4. The Lyα Line Profile

The resulting Lyα line profiles of the modeled MW Galaxy from $z \sim 14$ to $z \sim 6$ are shown in Figure 7. We randomly sample the frequency of the intrinsic Lyα photon from a Maxwellian distribution with the gas temperature at the emission location. All sources show asymmetric profiles with a single peak or weak double peaks. More interestingly, most profiles are shifted to shorter (bluer) wavelengths. This is a characteristic feature of gas inflow (Zheng and Miralda-Escudé 2002). Indeed, as shown in Figure 8, a significant fraction of the gas shows a large infalling velocity of $V_z \sim -100$ to $-200 \text{ km s}^{-1}$, even though our simulation includes feedback from stellar wind similar to that of Springel et al. (2005). In particular, the gas in the Galaxy from $z \sim 14 - 10$ is dominated by inflow motion, which explains the significant blueshift of the profiles in Figure 7 (top panel). At redshift $z \lesssim 8.5$, the gas exhibits outflow as well, and has a larger velocity distribution $-250 \lesssim V_z \lesssim 200 \text{ km s}^{-1}$ which results in an extended profile to both the blue and red wings. While asymmetric line profiles with an extended red wing are commonly seen in high-redshift LAEs, there appears to be some profiles in the $z \gtrsim 6$ observations that have complex features including double peaks and an extended blue wing, similar to what we see here (e.g., Ouchi et al. 2010; Hu et al. 2010; Kashikawa et al. 2011). The observed line of z8\_GND\_5296, the most distant LAE at $z = 7.5$, is not resolved well and thus has a Gaussian profile (Finkelstein et al. 2013). More observations of high-resolution Lyα line profiles of high-redshift LAEs are needed to test our model and verify our predictions.

We note that the Lyα line profile may be suppressed and changed by the intergalactic medium (IGM; e.g., Santos 2004; Dijkstra et al. 2007; Zheng et al. 2010; Laursen et al. 2011) because the IGM effectively scatters the Lyα photons at the line center and at shorter wavelengths by the Hubble flow (e.g., Laursen et al. 2011). As a result, the inflow feature in our profiles may disappear and the shape may become an asymmetric single peak with only photons at the red wing. Laursen et al. (2011) showed that a large fraction of Lyα flux from galaxies at $z \sim 6.5$ could be lost by scattering in IGM despite most of the IGM being ionized. As a simple test, we show the line profiles without photons at shorter wavelength as
shown in the blue dashed lines in the figure. As a result, about 0.59 (0.54) of the Ly\(\alpha\) flux from the galaxies at \(z = 12.1\) (6.2) are lost. The inflow feature completely disappears and the asymmetric profiles with the red wings may be recognized as the galaxies that have gas outflow. In addition, if IGM is highly neutral, even the Ly\(\alpha\) flux at the red wing is highly suppressed.

For neutral IGM, the IGM optical depth is estimated by

\[
\tau(D) \approx 2.3 \left( \frac{\Delta v}{600\; \text{km s}^{-1}} \right) \left( \frac{1+z}{10} \right)^{3/2} \quad \text{(Dijkstra & Wyithe 2010)},
\]

where \(\Delta v\) is the velocity shift from the line center. More than 0.99 of the Ly\(\alpha\) flux from our model galaxies is lost for the neutral IGM. Therefore, if the IGM is highly neutral, then the Ly\(\alpha\) flux from our model galaxies cannot be observed.

### 3.5. Detectability of Progenitors of Local \(L^*\) Galaxies

The emergent multi-wavelength SEDs of the MW Galaxy at different redshifts are shown in Figure 9. The shape of the SEDs evolves with redshift due to the change of intrinsic stellar radiation, absorption of continuum photons by gas and dust, and thermal emission by dust. In all cases, the strong Ly\(\alpha\) lines emerge, and at \(z \gtrsim 8.5\) the UV continuum at \(\lambda \lesssim 912\; \text{Å}\) in the rest frame is deeply declined due to strong absorption caused by dense neutral hydrogen gas around the star-forming region.

![Figure 8. Probability distribution function of the gas mass of the neutral hydrogen in the Galaxy as a function of radial velocity. The velocity is estimated from the center of mass of the galaxy in the radial direction.](image)

A major science goal of the two forthcoming telescopes, ALMA and JWST, is to detect the first galaxies. In order to predict the detectability of the infancy of a local \(L^*\) Galaxy, we contrast the SEDs with some detection limits of these two facilities in Figure 9. Our calculations show that the flux at 850 \(\mu\)m in the observed frame of the model Galaxy ranges from \(\sim 7.9 \times 10^{-5}\) mJy at \(z = 14.0\) to \(\sim 4.7 \times 10^{-2}\) mJy at \(z = 6.2\). With an array of 50 antennas and an integration of 10 hr, ALMA may be able to detect such galaxies at \(z \lesssim 8.5\) with a 3\(\sigma\) significance. However, since galaxies do not have many young stars and much dust at \(z \gtrsim 10\), observations in the continuum by ALMA become more difficult and it would need tens of hours of integration time. In contrast, JWST appears to be more powerful for detecting the earliest galaxies, such as the one we model here, because it can detect the UV continuum in the rest frame up to \(z \approx 12\). The Ly\(\alpha\) emission is strong even at \(z \approx 12\), which may be observable by the Near-Infrared Spectrograph (NIRSpec) on JWST. The NIRSpec will have a detection threshold of \(\sim 3 \times 10^{-18}\; \text{erg s}^{-1}\; \text{cm}^{-2}\) with \(R = 100\) and signal-to-noise ratio = 10 with an exposure time of 10\(^4\) s.

We note that in the above estimation, IGM absorption and transmission were not taken into account. The IGM can significantly suppress the Ly\(\alpha\) flux, and the transmission highly depends on the viewing angle (e.g., Laursen et al. 2011) by inhomogeneous ionization structures in the IGM (e.g., Abel et al. 2007; Yoshida et al. 2007; Jeeson-Daniel et al. 2012), which make the detection more difficult. Of course, the galaxies we present here represent progenitors of a local \(L^*\) Galaxy such as the Milky Way. Galaxies formed in highly overdense regions are likely much more massive (Li et al. 2007) and may be more easily detected by both ALMA and JWST (Y. Li et al. 2015, in preparation).

### 4. DISCUSSIONS

The gas inflow feature is present in our simulation with outflow from stellar feedback. In order to probe the effect of
Figure 9. Spectral energy distribution of the MW Galaxy at different redshifts and its detectability with JWST and ALMA. The open squares indicate the 10σ detection limits of JWST and ALMA with 16 antennas at integration times of 1 and 10 hr (from top to bottom), while the open triangles indicate the 3σ detection limits of JWST and ALMA with 50 antennas.

Figure 10. Same as in Figure 7, but here the simulation does not include the wind model from stellar feedback.
stellar wind on the gas inflow, we also performed the simulation with a pure thermal feedback model in which feedback from supernovae occurs only in thermal energy. In such a model, some fraction of the thermal energy can quickly escape as cooling radiation before conversion to kinetic energy. As a result, gas outflow does not occur efficiently.

The resulting Lyα line profiles and the probability distribution function of the neutral gas mass are shown in Figures 10 and 11, respectively. Without a strong outflow, the Lyα line profiles show a more pronounced blue wing. However, due to IGM transmission, the Lyα flux at the blue wing can be suppressed significantly. If Lyα photons at shorter wavelengths than the line center are suppressed, then 0.69 (0.44) of Lyα flux from the galaxies at $z = 12.1 (6.3)$ is lost (see the blue dash lines in Figure 10).

The galaxy in our simulation resides in a low overdensity region and it represents those that would evolve into present-day L* galaxies such as the MW, so it may not be the very first one formed in the universe. It is believed that the most massive halos in the highly overdense regions collapse first and are where the first stars form (e.g., Abel et al. 2002; Bromm & Larson 2004; Gao et al. 2007; Yoshida et al. 2008). These may also be the formation sites of the very first galaxies due to the feedback and chemical enrichment from PopIII stars, as well as an abundant gas supply (Li et al. 2007; Bromm et al. 2009).

One of the major limitations of our model is that the cosmological simulation does not have sufficient resolutions to follow the formation and evolution of individual stars. Instead, star formation is modeled using a “sub-grid” recipe based on the observed Schmidt–Kennicutt Law (Kennicutt 1998). Gas particles are converted into stars once they are cooled below $10^4$ K and the density is above a threshold (Springel & Hernquist 2003). Although this treatment is rather simplistic, it nevertheless provides a global star formation history close to what is believed of the MW Galaxy.

Another major limitation is that our current RT calculations do not include the propagation and scattering of Lyα and ionizing photons in the IGM. We make the prediction that galaxies with inflow of cold gas would result in asymmetric, blue-shifted Lyα line profiles. However, as discussed earlier, the absorption by IGM may change the profile to one with an extended red wing. We will study this issue in more detail in future work that includes the RT of Lyα and ionizing photons in the IGM.

5. SUMMARY

In this work, we have investigated the formation of a typical, nearby L' galaxy such as the MW and its Lyα properties at the earliest evolutionary stage. We combine a cosmological hydrodynamic simulation, which uses the Aquila initial condition and focuses on a MW-like galaxy with three-dimensional RT calculations using the improved ART2 code, which couples the multi-wavelength continuum, the Lyα line, and the ionization of hydrogen.

We find that the modeled MW Galaxy forms from efficient accretion of cold gas early on, which sustains a high SFR from $z \sim 14 - 6$. The cold accretion produces strong Lyα emission via collisional excitation, which has a luminosity ranging from $\sim 1.6 \times 10^{42}$ erg s$^{-1}$ at $z \sim 14$ to $\sim 5.5 \times 10^{42}$ erg s$^{-1}$ at $z \sim 6$. 
The escape fraction of the Ly\(\alpha\) photons increases from \(\sim 0.49\) at \(z \sim 6\) to \(\sim 0.81\) at \(z \sim 14\) due to less dust content at higher redshift. The EWs of the Ly\(\alpha\) lines increases with redshift, from \(\sim 93\) \AA\ at \(z \sim 6\) to \(\sim 2300\) \AA\ at \(z \sim 14\). Such high EWs may be due to significant contribution to Ly\(\alpha\) emission by excitation cooling, which dominates at high redshift. The resulting Ly\(\alpha\) lines exhibit asymmetric, mostly single-peak profiles shifted to the blue wing, a characteristic feature of inflow.

Furthermore, we demonstrate that the progenitors of local \(L^*\) galaxies such as that modeled here may be detected at \(z \lesssim 8\) by JWST and ALMA with a reasonable integration time. At higher redshift \(z \gtrsim 12\), however, only the Ly\(\alpha\) line may be observable by spectroscopic surveys with detection limits similar to JWST.

Our results suggest that the Ly\(\alpha\) line may be used to probe the formation, evolution, and gas properties of distant galaxies. It is perhaps one of the most powerful tools to detect the first generation of galaxies in the coming decade.

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