CHEMICAL ENRICHMENT IN DAMPED Ly\textsubscript{α} SYSTEMS FROM HIERARCHICAL GALAXY FORMATION MODELS

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ABSTRACT

We investigate chemical enrichment in damped Ly\textsubscript{α} (DLA) systems in the hierarchical structure formation scenario using a semianalytic model of galaxy formation. The model developed by Nagashima, Totani, Gouda & Yoshii takes into account various selection effects on high-redshift galaxies and can reproduce fundamental observational properties of galaxies, such as luminosity functions and number-magnitude/redshift relations. DLA systems offer the possibility of measuring metal abundance more accurately than faint galaxies. For example, recent measurements of the zinc abundance can help in understanding processes of metal pollution and star formation in DLA systems because zinc is virtually unaffected by dust depletion. Here we focus on this advantage for observations exploring the metallicity evolution in DLA systems at high redshifts. We can consistently show the metallicity evolution for reasonable models. The models also reproduce fundamental properties of the local galaxy population. This result suggests that the chemical evolution of DLA systems can be consistently reconciled with the observational features of typical galaxies. We also investigate other properties of DLA systems (column density distribution and mass density of cold gas) and find that star formation in massive galaxies should be more active than that in low-mass galaxies, which is consistent with the results of Nagashima et al. and Cole et al. in which the star formation timescale is set by the cold gas mass fraction in local spiral galaxies. Finally, we discuss host galaxies associated with DLA systems. We conclude from the observations that they primarily consist of sub-L\textsuperscript{*} and/or dwarf galaxies.

Subject headings: early universe — galaxies: formation — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

Absorption-line systems observed in the spectra of background quasars have proven to be a strong probe into the physical conditions (abundances of neutral gas and metals, kinematic properties, etc.) of the universe at high redshifts. In particular, damped Ly\textsubscript{α} absorption (DLA) systems, which have been associated with cold gas in protogalactic disks (Wolfe et al. 1986), provide some advantages in the investigation of various characteristics of primordial galaxies that are similar to faint ones at high redshifts. For example, we can obtain abundant data in the early universe from quasar spectra, which are less affected by observational limits caused by faintness of absorbers, chemical abundance, etc. Therefore, they have been studied extensively at redshifts 0 \leq z \leq 4.5 to explore physical processes in galaxies: star formation rates, abundances of metals and dust (Fall & Pei 1993; Lu et al. 1996; Pettini et al. 1997, 1999, 2000; Prochaska & Wolfe 1999, 2000), column density distribution (e.g., Storrie-Lombardi & Wolfe 2000; Rao & Turnshek 2000), and kinematics (Prochaska & Wolfe 1997, 1998). These observational features would provide important constraints on clarifying the evolutionary link between DLA systems and typical galaxies.

In particular, in DLA systems, we can measure abundances of various elements (Fe, Si, Ni, Mn, Cr, Zn, etc.) and thereby find good clues to the metallicity evolution of galaxies in the early universe. For example, relative elemental abundances are one of the most important components of this information, because abundance ratios of elements produced in different proportions by supernovae can provide independent insights into the chemical evolution. However, it has been difficult to establish some abundance patterns precisely (e.g., [α/Fe]) in DLA systems, because the level of depletion of refractory elements onto dust grains may be uncertain. For this reason, the zinc abundance has recently been recognized as a good tracer of the metallicity evolution instead of Fe\textsuperscript{ii}, because zinc is an undepleted element. Recent observations have generally reported that the absolute Zn abundance is ~10% of the solar value with no clear evolution over redshift (Pettini et al. 1997, 1999; Prochaska & Wolfe 1999; Vladilo et al. 2000). The low abundances and the apparent lack of redshift evolution have been interesting problems for considering DLA systems as protogalaxies, in particular, at low redshifts where abundances much closer to the solar ones are expected. This advantage of Zn measurement confirms that DLA systems so far remain one of the best probes at high redshifts into star formation history.

Recent theoretical studies focus on the nature of DLA systems and physical relations in galaxies observed at high and low redshifts. Katz et al. (1996) studied the formation of DLA and Lyman limit systems in a hierarchical clustering scenario using a hydrodynamical simulation of a CDM universe (Ω = 1). They concluded that the observed H\textsubscript{i} column density distributions can be reproduced within a factor of 2 if DLA systems are relatively massive and dense protogalaxies. They also showed that their model could reproduce the other

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properties of DLA observations. However, these results remain somewhat inconclusive. The calculations were restricted to a single CDM cosmology ($\Omega = 1$ CDM). In addition, they could not include galactic disks embedded in halos with circular velocities $V_c \leq 100$ km s$^{-1}$ because of their limited resolution ($M \sim 10^{11}$ h$^{-1} M_{\odot}$). Gardner et al. (1997a, 1997b, 2001) resolved these problems by using a relation between the absorption cross section $\sigma$ and the halo circular velocity $V_c$ obtained from numerical simulations. Assuming that the $\sigma V_c$ relation can be applied for previously unresolved halos, they presented numerical results for various cosmological models. As a result, the observed abundance of DLA systems can be reproduced if their extrapolation procedure applies to less massive halos ($V_c \geq 50$–$80$ km s$^{-1}$). However, the validity of their correction method remains uncertain. Therefore, their calculations could not include the contribution of DLA systems below their resolution limit, especially at redshifts $0 \leq z \leq 3$. Hahnelt, Steinmetz, & Rauch (1998, 2000) used kinematics to explore the nature of DLA systems in smoothed particle hydrodynamics (SPH) simulations with high resolution ($\sim$ a few kpc). They concluded that the large number of protogalactic clumps can reproduce the observed velocity width distribution and asymmetries of absorption lines found by Prochaska & Wolfe (1997, 1998). Their conclusion suggested that the majority of DLA systems are not large, rapidly rotating disks with $V_c \geq 100$ km s$^{-1}$ but protogalactic clumps with the typical circular velocity of DLA halos $V_c \sim 100$ km s$^{-1}$. Their numerical simulations showed that their models can reproduce observational properties of DLA systems and provided interesting insights into the nature of DLA systems.

Recently a different approach, semianalytic modeling, has been applied to deciphering the formation process of galaxies in the hierarchical clustering scenario (e.g., Kauffmann, White, & Guiderdoni 1993; Cole et al. 1994, 2000; Somerville & Primack 1999; Nagashima, Gouda, & Sugiura 1999; Nagashima et al. 2001, hereafter NTGY01; Nagashima et al. 2002). These approaches have some advantages. For example, semianalytic modelling can study the effect of star formation or supernovae feedback on galaxy evolution even under simple recipes. In addition, it does not suffer from resolution limitations. This approach can also take into account merging the histories of dark halos based on the power spectrum of the initial density fluctuation and has successfully provided galaxy formation models for reproducing observational properties of galaxies such as luminosity functions, the Tully-Fisher relation, the relation between the H i gas mass fraction and luminosities, and so forth. To understand the galaxy formation process, it is also important to focus on observational features of high-redshift galaxies. For example, faint galaxy number counts are good for constraining the key process of galaxy formation and the local features. NTGY01 confirms, using a similar semianalytic model, that the fundamental properties of local galaxies can be reproduced in a cosmological constant–dominated flat universe ($\Lambda$CDM model). Their model shows good agreement with the observational features of galaxies at high redshifts such as galaxy counts, after taking into account high-redshift selection effects caused by cosmological dimming of surface brightness, absorption by intergalactic H i gas, and internal dust absorption. Therefore, it is valuable to examine how improvements in the above model affect our predictions for the metallicity evolution of cold gas in high-redshift galaxies. Here we investigate the star formation history of DLA systems in our semianalytic model and whether we can consistently reproduce the metallicity evolution for the models that best match the observational constraints on local galaxy population. We also address what kinds of physical processes, such as star formation timescale, play key roles in the evolution of DLA systems within the framework of the semianalytic approach investigated here. Furthermore, we study other properties of DLA systems: H i column density distribution, mass density of cold gas, etc. Finally we discuss what kinds of galaxies are associated with DLA systems.

In § 2, we briefly describe the semianalytic model used here. In § 3, we show the evolution in chemical enrichment of DLA systems. In § 4, we present other properties of DLA systems in our calculation. Host galaxies of DLA systems are also discussed in § 4. Finally, we summarize our conclusions in § 5.

2. MODEL

We use the semianalytic model for galaxy formation from the work of NTGY01. As shown in NTGY01, our model reproduces luminosity functions, the cold gas mass fraction, and the disk radius of galaxies in the local universe and the faint galaxy number counts in the $\Lambda$CDM model.

For cosmological parameters, we adopt $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.015 h^{-2}$, $h = 0.7$ (where $h$ is the Hubble parameter, $h = H_0/100$ km s$^{-1}$ Mpc$^{-1}$), and $\sigma_8 = 1$, which is the normalization of the power spectrum of density fluctuation given by Bardeen et al. (1986). The cosmological parameters adopted here are consistent with recent observations, e.g., the Wilkinson Microwave Anisotropy Probe (WMAP) Spergel et al. (2003), while a slightly higher $\Omega_0$ has been favored recently. In this paper, we generally follow the model examined in NTGY01. In the following, we briefly describe aspects of the model.

The number density of progenitors of a dark halo as a function of their mass and redshift is given by an extended Press-Schechter model (Press & Schechter 1974; Bond et al. 1991; Bower 1991; Lacey & Cole 1993). The number of local halos follows the Press-Schechter mass function. The merging process of dark halos is given by the method developed by Somerville & Kolatt (1999) based on a Monte Carlo method. We focus on halos with circular velocity $V_c \geq 40$ km s$^{-1}$ and treat systems with small $V_c < 40$ km s$^{-1}$ as diffuse accretion mass.

We assume that baryonic gas consists of two phases: cold and hot. When a halo collapses, halo gas is assumed to be shock-heated to the virial temperature of the halo and distributed in a singular isothermal sphere (hot gas). The cold gas is defined as the gas component within a “cooling” radius in which hot gas cools quickly. Only a “central” galaxy in a halo accretes the cold gas. The cold gas then becomes available for star formation. The star formation process can play an important role in chemical enrichment of cold gas. The star formation rate (SFR) is assumed as

$$\dot{M}_* = \frac{M_{\text{cold}}}{\tau_*},$$

where $M_*$ and $M_{\text{cold}}$ are the mass in stars and cold gas, respectively, and $\tau_*$ is the timescale of star formation. Because the star formation process has large uncertainties, it is conceivable that the SFR has more than one timescale. In our model, we assume two types of star formation timescale:
constant star formation (CSF) and dynamical star formation (DSF) as follows

\[
\tau_s = \begin{cases} 
\tau_0^0 \left( \frac{V_c}{V_*} \right)^{\alpha_s} & \text{CSF}, \\
\tau_0^0 \left( \frac{V_c}{V_*} \right)^{\alpha_s} \left[ \frac{\tau_{\text{dyn}}(z)}{\tau_{\text{dyn}}(0)} \right] & \text{DSF}.
\end{cases}
\]

(2)

Note that these two correspond to the constant efficiency (CE) and accelerated efficiency (AE) models, respectively, in Somerville, Primack, & Faber (2001). For the CSF model, the star formation timescale is constant at all redshifts \( z \). For the DSF model, the timescale is proportional to the dynamical time of disks, \( \tau_s \propto \tau_{\text{dyn}}(z) \), which becomes shorter as redshift increases. Following Cole et al. (1994, 2000) and NTGY01, we also take into account the dependence of the star formation timescale on the circular velocity, \( \tau_s \propto V_c^{\alpha_s} \). We adopt the LC and LD models in NTGY01 as reference models in which the star formation timescales are given by \( \tau_0^0 \left( \frac{V_c}{V_*} \right) = (1.5 \text{ Gyr}, 300 \text{ km s}^{-1}) \) for CSF and \( (4 \text{ Gyr}, 200 \text{ km s}^{-1}) \) for DSF, respectively. Actually these parameters are determined by matching the cold gas mass fraction of spiral galaxies to that observed. Therefore, these parameters are also expected to play an important role in determining the observable characteristics of DLAs systems. It should also be noted that we here explore two types of star formation timescale according to the notation defined by Somerville & Primack (1999). One is the “Durham model” in which the star formation timescale depends only on circular velocity (Cole et al. 1994), and another is the “Munich model” in which it depends only on redshift (Kauffmann et al. 1993). Thus, the star formation timescale is here assumed to totally depend on the halo circular velocity and redshift. For chemical enrichment, we take the metal yield \( y = 0.038 \) adopted by NTGY01.

Supernova explosions also affect galaxy evolution. We follow here a recipe for the supernova feedback process formulated in NTGY01: the reheating rate of cold gas by supernova explosions is assumed to be proportional to the SFR

\[
\dot{M}_{\text{reheat}} = \left( \frac{V_c}{V_{\text{hot}}} \right)^{-\alpha_{\text{hot}}} \dot{M}_*,
\]

(3)

where the values of the parameters \( V_{\text{hot}} = 280 \text{ km s}^{-1} \) and \( \alpha_{\text{hot}} = 2.5 \) are required to reproduce the observed luminosity function of local galaxies in LC and LD models in NTGY01. Note that the conclusions in the previous work show that the supernova feedback process is tightly coupled to the shape and normalization of the luminosity function of local galaxies.

When two or more halos merge, the central galaxy in the largest progenitor halo becomes the new central one. All other galaxies, called “satellite galaxies,” remain around the center. After each halo merging, we consider the following two mechanisms for mergers of galaxies: dynamical friction and random collision. Satellite galaxies merge with the central one on the dynamical friction timescale. Between satellite galaxies, random collisions also occur on the mean free timescale. When two galaxies merge, if the mass ratio of the smaller galaxy to the larger one is larger than \( f_{\text{ridge}} \), a starburst occurs and all cold gas is consumed (major merger). Then all the stars are in a spheroidal component. Otherwise, the smaller one is simply absorbed into the disk of the larger one with no additional star formation activity (minor merger). We summarize the parameter sets adopted for LC and LD models in Table 1 (the other parameters are the same as in NTGY01).

Finally, we define DLA systems in our model. We simply assume that all DLA systems have gaseous disks that are face-on to us (the inclination effect will be discussed in §4) and that the radial distribution of H\textsc{i} column density follows an exponential profile, \( N_{\text{H}1}(r) = N_0 \exp \left( -r/r_c \right) \), where \( N_0 \) is the central column density of neutral gas and \( r_c \) is the effective radius of the gaseous disk. We assume the effective radius \( r_c = r_0(1+z) \), where \( r_0 \) is the radius provided by specific angular momentum conservation of cooling hot gas (Nagashima et al. 2002). According to Nagashima et al. (2002), the specific angular momentum of halos has a lognormal distribution in terms of the so-called nondimensional spin parameter \( \lambda \) but with a somewhat large mean and dispersion, \( \lambda = 0.06 \) and \( \sigma_\lambda = 0.6 \). The central column density \( N_0 \) is given by \( N_0 = M_{\text{cold}}/(2\pi\mu m_p r_c^2) \), where \( m_H \) is the mass of a hydrogen atom and \( \mu(=1.3) \) is the mean molecular weight. The size of DLA systems is defined by the radius \( R \) at which \( N_{\text{H}1} = 10^{20} \text{ cm}^{-2} \). For each system, we take the column density averaged over radius within \( R \).

3. CHEMICAL ENRICHMENT IN DLA SYSTEMS

Figure 1 shows the metallicity evolution of cold gas in DLA systems. The solid line shows a result for the LC model (\( \chi = 1.5 \text{ Gyr} \) and \( \alpha_s = -2 \)). We compare our results here with the data given by Prochaska & Wolfe (2000) and Savaglio (2001). Savaglio (2001) evaluates the metallicities of DLA systems by adopting a dust correction and shows ranges of the metallicity as a function of redshift (0 \( \leq z \leq 4.5 \)). Our calculations show that the mean metallicity increases gradually from \( 0.03 \) to solar abundance at redshift \( z \sim 3 \) to one-half at

\[ \text{TABLE 1}
\begin{tabular}{lcccccc}
\hline
CDM & Cosmological Parameters & & & & & \\
Model & \( \Omega_0 \) & \( \Omega_\Lambda \) & \( h \) & \( \sigma_8 \) & \( V_{\text{hot}} \) & \( \alpha_{\text{hot}} \) & \( \chi_{\text{hot}} \) & \( f_{\text{ridge}} \) \\
\hline
LC & 0.3 & 0.7 & 0.7 & 1 & 280 & 2.5 & 1.5 & 2 & 0.5 \\
LD & 0.4 & 0.7 & 0.7 & 1 & 280 & 2.5 & 4 & 2 & 0.5 \\
SC & 1 & 0 & 0 & 0.6 & 320 & 5.5 & 4 & 3.5 & 0.2 \\
OC & 0.3 & 0 & 0.6 & 1 & 220 & 4 & 1 & -3 & 0.5 \\
\hline
\end{tabular}
\]
the present because of ongoing star formation with constant efficiency. The metallicity evolution shows good agreement with the observations over the whole range of redshifts. Thus, the LC model can reproduce the metallicity evolution of DLA systems, as well as many galactic properties such as luminosity function and galaxy counts. Note that the dotted line indicating mean stellar metallicity nearly traces that of cold gas, because cold gas is the direct material precursor of stars.

The efficiency of star formation plays a key role in the metallicity evolution of DLA systems. In Figure 1, we also present a result for the LD model (dashed line) in which the star formation timescale is proportional to the dynamical time of disks, i.e., the SFR is higher at high redshifts. The resultant curve for the LD model is very shallow (1/10 solar abundance at $z = 5$), because the SFR is much larger at high redshifts than that of the LC model. Therefore this model results in metallicities somewhat more abundant than to the high-redshift data. We thus conclude that the star formation timescale should be nearly constant in order to obtain good agreement with the observed data for both DLA systems and local galaxies.

Now we explore the dependence of the chemical enrichment on the star formation process. Figures 2a and 2b depict the effects of changing $\tau_0$ and $\alpha_s$, respectively, on chemical enrichment. The metal abundance strongly depends on $\tau_0$ and $\alpha_s$, as well as on the cold gas mass fraction of galaxies (see Fig. 9 in Cole et al. 2000). Figure 2a shows the dependence on $\tau_0$ in the LC model. As the star formation timescale is shorter (SFR is larger), the average metallicity becomes higher through metal enrichment. In addition, we show the dependence on $\alpha_s$ of metallicity in Figure 2b. Unlike the model with $\alpha_s = 0$, which roughly corresponds to the “quiescent model” in Somerville et al. (2001), the LC model with $\alpha_s = -2$ can produce DLA systems with low metallicities ($\sim 1/10 Z_\odot$) at high redshifts, because the negative value of $\alpha_s$ decreases the SFR in low-mass galaxies, which are numerous and have generally low metallicities, and leads them to be identified as DLA systems because of their increasing gas fraction. Therefore, our results are different from those found in Somerville et al. (2001) in which DLA systems have higher metallicities for cold gas than observations of high-redshift systems indicate. We also checked the dependences of our results on other parameters such as the SN feedback-related parameters $V_{\text{hot}}$ and $\alpha_{\text{hot}}$ and found that they only weakly affect metallicity evolution. Thus, from these figures, we find that the metallicity evolution of DLA systems can be
consistently reproduced by the LC model. We see that the LC model also successfully reproduces the column density distribution in § 4.

Next, in Figure 2c, we present results not only for LC but also for the standard CDM (SC) and an open CDM (OC). Astrophysical parameters for SC and OC models are normalized in the same manner as LC and LD models, as determined by local galaxy properties (Table 1). The baryon density parameter $\Omega_b = 0.015 h^{-2}$ is adopted for all models. The value of $\sigma_8$ is normalized by the cluster abundance for models LC and OC. Note that NTGY01 found that LCDM is favoured by the observed Hubble Deep Field (HDF) galaxy counts. Figure 2c shows that the LC model best predicts the observed gas metallicity among these cosmological models at all redshifts. While both SC and OC models completely underpredict the observed metallicities, the LC model exhibits milder evolution at high redshifts compared to the SC model and shows good agreement with the observations. Thus, from the metallicity evolution of DLA systems, low-density universes are favored.

4. GLOBAL PROPERTIES OF DLA SYSTEMS

In this section, we focus on the $H\alpha$ column density distribution of DLA systems, because we need to confirm that the gas systems selected here are indeed DLA systems. In Figure 3, we show the differential distribution $f(N_{HI}, X(z)) = d^2N/dN_{HI}dX$, which denotes the number per unit column density $N_{HI}$ and per unit absorption distance $X(z)$ (Bahcall & Peebles 1969). The data points are taken from Storrie-Lombardi & Wolfe (2000). This result is averaged over redshifts $0 \leq z \leq 5$. The solid line shows the result for the LC model. The column density distribution is in good agreement with the observational data. Alternatively, we present a result for the LD model (dashed line) in Figure 3. In this case, DLA systems are deficient over the whole range of column density. The LD model has a shorter timescale of star formation in which cold gas turns into stars more rapidly than the LC model at high redshift. Therefore, the LD model predicts a smaller number of DLA systems than the LC model. Thus, the efficiency of star formation also plays an important role in the column density distribution.

It is also interesting to investigate the effect of the inclination of the galactic disk. The inclination-averaged cross section is half as much for random orientations, although here we assume that all disks are face-on to us. This corresponds to $\theta = 60^\circ$ when a disk is viewed at an angle $\theta$ to the normal. We therefore calculate the column density distribution for viewing angles: $\theta = 0^\circ$, $30^\circ$, and $60^\circ$. Figure 4 shows how the differential distribution depends on the inclination. We find that the slope in the distribution is a little flatter when the viewing angle becomes larger, because the cross section becomes small and the averaged $N_{HI}$ increases with the inclination. However, the differences between the results are small ($\leq 0.1$ dex) in the observed range of column density ($N_{HI} > 10^{20.3}$ cm$^{-2}$). Therefore in this paper, we assume all galaxies are face-on because of the small dependence on the inclination.

To investigate the number evolution of DLA systems, in Figure 5, we also show the differential distribution at four redshifts, $z = 1, 2, 3,$ and 4. The observational data are from Storrie-Lombardi & Wolfe (2000). In Figure 5a (open circles), we also take additional data reported by Rao & Turnshek (2000), which include a sample at low redshift, $z \sim 0.8$. We find that our results are generally consistent with the observations. Storrie-Lombardi & Wolfe (2000) and Rao & Turnshek (2000) also pointed out that the slope in differential distributions is more moderate at lower redshifts. This signature has interesting implications for the formation of DLA systems. However, it is still controversial to address the redshift evolution of $f(N_{HI}, X)$ systematically, because the samples are
not large. While the LC model can provide a reasonable fit to observations, low-$N_{\text{HI}}$ systems are slightly deficient at redshift $z = 4$. Although we need more observations to see whether this deficiency could be serious, this might require some mechanism for enlarging the cross section such as galactic winds pushing gas out far away from central disks.

Previously, Maller et al. (2001) investigated the radial distribution of cold gas in DLA systems at high redshifts using a semianalytic model given by Somerville et al. (2001). They found that a Mestel distribution can reproduce column density distributions better than single-disk models (also including an exponential distribution) based on angular momentum conservation. Although Maller et al. (2001) required number suppression of DLA systems in order to match the kinematic data, the single-disk models fail to reproduce the column density distributions because DLA systems have a short radial extent so the cross sections are too small. Figure 3 also shows results for the same model as the LC model but for $\alpha_* = 0$ (dotted line). This model roughly corresponds to one in which the radial distribution of column density is of an exponential type (Maller et al. 2001, see their Fig. 4). Compared with this result, our LC model predicts that DLA systems are more abundant, especially for low-$N_{\text{HI}}$ systems, because the negative $\alpha_*$ suppressed star formation in low-$V_c$ systems (see below, Fig. 8). Therefore the number density is consistently high enough to reproduce column density distributions of DLA systems even in those in which the radial distribution of $\text{HI}$ column density follows an exponential profile.

Generally, in Figures 3 and 5, we conclude that the LC model in our calculation can reproduce fundamental properties of DLA systems, both their metallicity evolution and the column density distribution, so we investigate other properties of DLA systems in the LC model below.

Figure 6 shows the mass density in $\text{HI}$ gas contributed by DLA systems. The observed data are given by Storrie-Lombardi & Wolfe (2000) and Rao & Turnshek (2000). Our results show that the evolution of mass density is generally similar to that calculated from observations. However, the calculated density is higher than the observed data at $z > 2$. As discussed above, the metallicity is generally higher at low redshifts (Fig. 1). This might stem from the fact that dusty systems are abundant at present and systematically fail to be identified as DLA systems. Therefore, local observations show only the lower limits of mass density in cold gas systems. Furthermore, mass density is very sensitive to the number of high-$N_{\text{HI}}$, systems, if the power-law index $\beta (f \propto N_{\text{HI}}^{-\beta})$ is less than 2. At $z \leq 2.5$, the small number statistics of high-$N_{\text{HI}}$, systems makes assessment of the mass density more uncertain, as differences in error bars of observational data between low and high redshifts in Figure 6 show. A larger sample at $z > 2.5$ would determine the data with sufficiently small errors to permit comparison with the high-redshift data.

Figure 7 shows the average mass evolution of each phase. While cold-gas mass is almost constant with redshift, stellar mass increases gradually toward the present because star formation proceeds to accumulate stellar mass and the
merging process continues to form massive systems. At $z \sim 1$, the stellar mass exceeds that of cold gas and finally attains 10 times that of cold gas at the present. We also calculate mass-weighted metallicities of cold gas in both DLA systems and all galaxies. The results are shown in Figure 7. Like the evolution of metal mass, the metallicity increases gradually toward the present. Furthermore, the metallicities of cold gas in both DLA systems and all galaxies are quite similar. This indicates that the chemical enrichment in DLA systems is similar to that in all galaxies.

Finally, we focus on what kinds of systems are identified as DLA systems. Figure 8 depicts the average circular velocity of DLA systems at $0 \leq z \leq 5$. Like the mass evolution, the average circular velocity increases toward low redshifts as merging proceeds, and typical velocities are $V_c \sim 60 \text{ km s}^{-1}$ at $z \sim 3$ and $V_c \sim 90 \text{ km s}^{-1}$ at $z \sim 0$. Figure 9 shows the distribution of circular velocities; Figures 9a–9d present the number fraction of galaxies identified as DLA systems as a function of circular velocity at redshifts $z = 0, 1, 3,$ and $5$, respectively. From these results, it is apparent that the dispersion of the $V_c$ distribution increases gradually toward low redshifts, like the average of the circular velocity. This implies that massive DLA systems form predominantly through galaxy mergers at low redshifts. At present, $\sim 5\%$–$10\%$ of DLA systems can be massive systems like our Galaxy, while gaseous disks like the Milky Way rarely give rise to DLA systems at high redshifts $z \geq 3$. This result indicates that DLA systems are more likely to be found in less massive halos than in typical $L^*$ spirals. We find that this picture is in strong conflict with the classical one in which DLA systems are relatively massive galaxies like our Galaxy.

Figure 10 shows absolute luminosity evolution (in $U$, $B$, $V$, and $K$ bands) of median host galaxies identified as DLA systems. Like stellar mass, luminosity gradually increases with star formation. At present, the average luminosities are $L(B) \sim 2 \times 10^9 L_\odot(B)$ and $L(K) \sim 10^{10} L_\odot(K)$, comparable with dwarf galaxies. Considering the other results from our calculation, we find that host galaxies of DLA systems primarily consist of sub-$L^*$ and/or dwarf galaxies. Recently, Cen et al. (2003) investigated the metallicity evolution of DLA systems using a hydrodynamic simulation. They found that DLA systems in the simulation provide good matches to observational data for the metallicity evolution, the column density distribution, the redshift evolution of the neutral gas content, etc. Simultaneously, they also stressed that DLA systems comprise a mix of various morphological types.
including systems less massive than present-day $L^*$ galaxies, and showed that the median DLA system typically shows
absolute luminosities of $L = 0.1L^*(z = 0)$ at $z = 3$ and $L = 0.5L^*(z = 0)$ at $z = 0$. This shows good agreement with our result and also suggests that DLA systems are primarily composed of faint galaxies. Moreover, *Hubble Space Telescope* (HST) and ground-based observations directly image of DLA systems at $z \leq 1$. The results suggest that DLA systems might contain mixed types of galaxies and that a number of the systems are dwarf galaxies and/or compact objects (e.g., Rao & Turnshek 1998).

So far, the nature of DLA systems still remains controversial. In principle, DLA systems have a large column density in neutral hydrogen, $N_{\text{HI}} \gtrsim 10^{20}$ cm$^{-2}$, comparable to the surface density of present-day spiral galaxies. This suggests the possibility that DLA systems arise from galactic large disks (Wolfe et al. 1986). Moreover, Prochaska & Wolfe (1997, 1998) found that absorption lines of low-ionization ionic species in DLA systems show large velocity spreads and partly asymmetric profiles. They also argued that the observed kinematics can be reproduced by massive rotating disks. Alternatively, Haehnelt et al. (1998) showed that the majority of DLA systems are protogalactic clumps (typical circular velocity $V_c \sim 100$ km s$^{-1}$) by using hydrodynamic simulations within the hierarchical structure formation scenario. They also stressed that the asymmetries and large velocity spreads of absorption lines associated with DLA systems can be reproduced by complex geometry and nonequilibrium dynamics of neutral gas embedded in dark halos that are not necessarily virialized. In the present work, we focus on the virialized systems; the effects of nonequilibrium dynamics of clumps are neglected, but might be important. Further investigations will be required to clarify the kinematics of DLA systems in detail. A significantly larger sample than that available at present, $\sim 50$, is needed to discuss the kinematic data of DLA systems statistically.

Figure 11 shows the cross sections $\sigma_{\text{DLA}}$ as a function of circular velocity $V_c$ at redshifts $z = 0, 1, 3,$ and $5$. These results suggest that DLA systems have a typical size $\sim 10$ kpc at $V_c \sim 200$ km s$^{-1}$. When these relations are fitted by a power law, $\sigma_{\text{DLA}} \propto V_c^\beta$, we find that $\beta \sim 1$ for each panel and that $\beta$ increases slightly as redshift decreases. This relation has been investigated in hydrodynamic simulations. For example, Gardner et al. (2001) showed steep scaling, $\beta \sim 1.5$, for a LCDM model. Recent SPH simulations similarly found $\beta \sim 2$ (Haehnelt et al. 2000; Nagamine, Springel, & Hernquist 2003). While the steepness of the $\sigma_{\text{DLA}}-V_c$ relations in our model are similar to that in numerical simulations, the average cross section in our results is smaller than the numerical ones. Such large cross sections in simulations may arise from two reasons. First, the limited resolution prevents us from resolving DLA systems with large cross sections, because they have cross sections smaller than numerical resolutions. Some simulations have predicted that DLA systems have quite large disks, e.g., $\sim 100$ kpc at $V_c \sim 200$ km s$^{-1}$. Second, a large cross section can be produced by neutral gas with complex geometry
or nonequilibrium dynamics induced by frequent merging of protogalactic clumps. It is also produced even by numerical simulations with high resolution while the average cross section is small, \( \sim 17 \) kpc at \( V_c \sim 200 \) km s\(^{-1}\) (Haehnelt et al. 2000). Therefore, the different sizes from numerical simulations may mainly stem from neglecting the latter effect.

5. CONCLUSIONS

We investigated the metallicity evolution of DLA systems in a hierarchical galaxy formation scenario using a semi-analytic galaxy formation model given by NTGY01, which has been found to show good agreement with many properties of galaxies. In previous theoretical work, it has been claimed that the metallicity of DLA systems is too high to reproduce those observed (e.g., Somerville et al. 2001). We find that, in contrast to previous work, DLA systems in our model have low metallicity, \( \sim 10^{-2} Z_\odot \), consistent with observational data when we use the same model given by NTGY01 that reproduces many observations of local and high-redshift galaxies. This conclusion results from setting the star formation timescale as follows: (1) nearly constant with redshift and (2) a longer timescale in lower circular velocity systems. Our results suggest \( \tau_s \propto V_c^{-\alpha_s} \) and \( \alpha_s = -2 \), which is entirely consistent with NTGY01. The first assumption indicates that there is a large amount of cold gas at high redshift. The second indicates that a stronger \( \alpha_s \) dependence causes a low star formation rate in low-mass galaxies that contribute more to the total number of DLA systems. These points lead to the result that DLA systems have low metallicity (\( Z \sim 10^{-2} Z_\odot \)), consistent with observational data.

We can also reproduce column density distributions even under the assumption that the radial distribution of H\(_I\) column density follows an exponential profile. In addition, with our results for the average circular velocities and absolute luminosities, our calculation indicates that DLA systems are primarily composed of less massive systems rather than present-day \( L^* \) galaxies. In a subsequent paper, we intend to investigate in detail host galaxies of DLA systems in our model, including comparisons with observational properties of dwarf galaxies and/or other types of galaxies.

In further analyses, the following effects might be considered. First, in our model, the metal enrichment of cold gas is tightly coupled with star formation, because we assume here that the metal ejected by stars is completely mixed with cold gas and finally becomes distributed throughout the disk. However, it is preferable to consider that galactic disks generally have metallicity gradients: outer regions may be metal-poor unlike the metal-rich inner regions (Pagel 1997; Taylor 1998). Second, the metal distribution might not be consistently diffuse. Chengalur & Kanekar (2000) pointed out that typical DLA systems have a multiphase medium composed of cold and warm H\(_I\) gas, which is shown by the observational fact that the spin temperatures of the H\(_I\) 21 cm transition, which correspond to the kinetic temperature, appear to be
higher \((T \gtrsim 1000 \text{ K})\) than those typical \((T \sim 100–200 \text{ K})\) of the Milky Way or nearby spiral galaxies. Moreover, Kanekar, Ghosh, & Chengalur (2001) and Lane, Briggs, & Smette (2000) found that, in two DLA systems at low redshifts, a large amount of neutral gas is in the warm phase from spectra fitted by multiple components with various spin temperatures. The inhomogeneous gas may arise from the wide range of metallicity in present DLA systems. Moreover, local observations show that dusty systems generally have larger abundances. In practice, dusty DLA systems systematically fail to be observed because dust in DLA systems dims background quasars. These problems are clearly issues that deserve further investigation. In future, the combination of accurate dust correction using various elements and detections of more DLA systems, especially at \(0 \lesssim z \lesssim 1\), are expected to reveal the origin of DLA systems and the star formation history at high redshifts.

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