DAMPED Lyα ABSORBING GALAXIES AT LOW REDSHIFTS z ≤ 1 FROM HIERARCHICAL GALAXY FORMATION MODELS

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ABSTRACT

We investigate damped Lyα absorbing galaxies (DLA galaxies) at low redshifts (z ≤ 1) in the hierarchical structure formation scenario. In our previous paper, we showed that our model of galaxy formation can explain basic properties of DLA systems such as the metallicity evolution and H i column density distribution. As a subsequent study, we focus on low-redshift DLA systems in detail and compare recent data of many characteristics and their relationships, such as the luminosities, H i column densities, and sizes of galaxies with H i column densities large enough to produce DLA absorptions obtained by optical/radio observations. While there has been debate about what types of galaxies correspond to DLA systems, by using a theoretical model that simultaneously treats both DLA systems and galaxies, we clarify the nature of low-redshift galaxies that produce DLA absorptions, because observational data of such galaxies, mainly at low redshifts, are currently available. We find that our model well reproduces the distributions of fundamental properties of DLA galaxies such as the luminosities, column densities, and impact parameters obtained by optical and near-infrared-imagings. Our results suggest that DLA systems primarily consist of low-luminosity galaxies with small impact parameters (typical radius ~3 kpc, surface brightness from 22 to 27 mag arcsec−2) similar to those of low surface brightness (LSB) galaxies. In addition, we investigate selection biases arising from the faintness of DLA systems and from the masking effect, which prevents us from identifying a DLA galaxy hidden or contaminated by the point-spread function of a background quasar. We find that the latter affects the distributions of DLA properties more seriously than the former and that the observational data are well reproduced only when the masking effect is taken into account. The rate of DLA galaxies missed because of the masking effect reaches 60%–90% in the sample at redshifts 0 ≤ z ≤ 1 when an angular size limit is as small as 1″. Furthermore, we find a tight correlation between H i mass and a cross section of DLA galaxies, and we also find that H i–rich galaxies with M_HI ~ 10^9 M☉ dominate DLA systems at z ~ 0. These features are entirely consistent with those from the Arecibo Dual-Beam Survey, which is a blind 21 cm survey. Finally, we discuss star formation rates and find that they are typically about 10^{-2} M☉ yr^{-1}, as low as those in LSB galaxies.

Subject headings: galaxies: evolution — galaxies: formation — quasars: absorption lines — radio lines: galaxies

1. INTRODUCTION

The numerous absorption lines found in quasar spectra are one of the few observational opportunities that provide us fruitful information on the physical state of the evolving universe. These absorption lines offer several advantages over emission lines. For example, the line features reflect the physical state of the astronomical objects and the intergalactic medium. Another advantage comes from the fact that absorption lines are free from observational limitations of the detection of absorbers caused by their faintness in photometric surveys.

Among those absorption-line systems, damped Lyα (DLA) systems provide exceptional insights into exploring galaxy formation. DLA systems have been interpreted as arising from cold gas in galactic disks along the lines of sight to quasars (Wolfè et al. 1986). So far, some observational facts on DLA systems have been obtained from detailed studies of quasar absorption spectra: for example, (1) the H i column densities are similar to those in our Galaxy, (2) most of them have low metallicities, ~1/10 Z⊙ (e.g., Prochaska et al. 2003), and (3) the H i column density distributions are as well fitted by a single power law as those of the Lyα forest (e.g., Storrie-Lombardi & Wolfe 2000; Péroux et al. 2003). These facts suggest that DLA systems are galaxies in an early evolutionary stage. Therefore, it would be interesting to know whether theoretical models of galaxy formation can consistently account for fundamental properties of DLA systems.

Furthermore, some low-redshift DLA systems can also be directly observed in recent photometric surveys. These samples provide a clue to revealing what types of intervening galaxies (hereafter referred to as “DLA galaxies”) cause DLA lines in quasar spectra. Such low-redshift DLA galaxies have been studied from both direct photometric images and spectroscopic follow-ups (e.g., Steidel et al. 1994, 1997; Lanzetta et al. 1997; Le Brun et al. 1997; Fynbo et al. 1999; Rao & Turnshek 1998; Turnshek et al. 2001; Bouché et al. 2001; Bowen et al. 2001; Warren et al. 2001; Möller et al. 2002, 2004; Rao et al. 2003; Chen & Lanzetta 2003; Schulte-Ladbeck et al. 2004). The results of these searches suggest that DLA systems have a wide range of the morphology, from dwarf to spiral galaxies, and do not comprise a single population as do normal spiral galaxies. This picture is rather consistent with what is expected from the hierarchical structure formation scenario based on cold dark matter (CDM) models, because those predict that galaxies can span the range of morphological types.
from dwarfs to massive spiral galaxies. So it is clearly valuable to compare the observed properties of DLA galaxies with those predicted by theoretical models as a useful test of theories of galaxy formation.

Semianalytic modeling has been applied with a view to deciphering the clues to the formation process of galaxies in the hierarchical clustering scenario. This approach takes into account merging histories of dark halos based on the power spectrum of the initial density fluctuation, and it has successfully provided galaxy formation models for explaining observational properties of galaxies such as luminosity functions, the relation between the H i gas mass fraction and luminosities, and so forth. It has some advantages over numerical hydrodynamic simulations. For example, it can clarify the effect of star formation or supernovae feedback on galaxy evolution even under simple recipes. Moreover, it does not suffer from resolution limitations in numerical hydrodynamic simulations. This is important for studying the formation process of small objects that are difficult to resolve by numerical simulations. Therefore, it is valuable to apply this model to studying the evolution of DLA systems that tightly correlate with galaxies. So far, several semianalytic models have been developed and provide interesting results on the physical relations between DLA systems and galaxies (Kauffmann 1996; Somerville et al. 2001; Maller et al. 2001, 2003; Okoshi et al. 2004, hereafter Paper I). In Paper I we focused on the metallicity evolution and the H i column density distribution and concluded that DLA systems primarily consist of dwarf and/or sub-\(L^*\) galaxies. As a subsequent study, this paper expands on these previous results to reveal the nature of low-redshift DLA systems by exploring the typical properties of DLA galaxies obtained by recent observations. Here the following advantages of this study should be addressed. (1) Our model can reproduce the main properties of DLA systems, that is, the metallicity evolution and the H i column density distribution. (2) Our model incorporates various effects that affect the detection of DLA galaxies: cosmological dimming of the surface brightness, internal dust absorption, and the observational bias caused by glare of quasars behind DLA galaxies along lines of sight. (3) Our model can also reproduce many of the results of galaxy population observations, such as the luminosity functions and number counts (see Nagashima et al. 2001). This is the first theoretical study to use a hierarchical galaxy formation model to explore the photometric and radio properties of low-redshift DLA galaxies comprehensively enough to compare with the currently available observations.

In § 2 we briefly describe our model. In § 3 we show the results for various properties of DLA galaxies. In § 4 we discuss the selection biases for the detection of DLA galaxies. In § 5 we explore some possibilities for studying the nature of DLA galaxies. We focus on the radio properties of DLA systems. We also discuss the star formation rate in DLA galaxies, which can be a good tracer for discerning what types of galaxies compose the population of DLA systems. Finally, in § 6 we summarize our conclusions and compare our results with other observations.

2. MODEL

The semianalytic model of galaxy formation used here is based on CDM models in which, assuming a power spectrum of initial density fluctuations, dark halos emerge from the density fluctuations, cluster gravitationally, and merge together. Gas in dark halos cools and then forms stars. Such processes lead to the formation of the galaxies that comprise the gas and stars embedded in dark halos. After galaxies form, some galaxies, such as our own, become massive via merging processes. We apply this scenario to studying the nature and formation of DLA systems in a semianalytic modeling framework. The semianalytic model of galaxy formation used here is the same as the LC model described by Paper I, which well reproduces the observed number distributions and metallicity evolution of DLA systems. This model also well reproduces many of the observed properties of galaxies, such as luminosity functions, cold gas mass fractions, disk sizes, and faint galaxy number counts in a \(\Lambda\)CDM model (Nagashima et al. 2001). We provide an outline of this model below.

The cosmological parameters that we adopt are \(\Omega_0 = 0.3\), \(\Omega_{\Lambda} = 0.7\), \(\Omega_b = 0.015\) h\(^{-2}\), h = 0.7 (where h is the Hubble parameter, \(h = H_0/100\) km s\(^{-1}\) Mpc\(^{-1}\)), and \(\sigma_8 = 1\), that is, the normalization of the power spectrum of density fluctuations given by Bardeen et al. (1986). The number density of dark halos at present is given by the Press-Schechter mass function (Press & Schechter 1974). The past merging history of each dark halo is realized by a Monte Carlo method proposed by Somerville & Kolatt (1999), which is based on an extended Press-Schechter formalism (Bond et al. 1991; Bower 1991; Lacey & Cole 1993). Only halos with circular velocities \(V_{\text{circ}} \geq 40\) km s\(^{-1}\) are identified as isolated halos, and others are regarded as the diffuse accretion mass.

We assume that baryonic gas consists of two phases: cold and hot. The gas in a halo should be shock-heated to the virial temperature of the halo after the halo collapses. The heated gas is defined as hot gas in our model. A part of the hot gas cools quickly by radiative cooling and falls to the gaseous disks; this is defined as cold gas. The cold gas then becomes available for star formation. The star formation rate (SFR) is assumed to be

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

where \(\dot{M}_*\) and \(M_{\text{cold}}\) are the masses in stars and cold gas, respectively, and \(\tau_*\) is the timescale for star formation. We assume a star formation timescale independent of the redshift as follows:

\[
\tau_* = \tau_0^\alpha \left(\frac{V_{\text{circ}}}{300 \text{ km s}^{-1}}\right)^\alpha.
\]

The free parameters \(\tau_0^\alpha\) and \(\alpha\) are chosen by matching the model prediction of cold gas mass fractions of spiral galaxies to the one observed, because those directly determine the gas consumption rate. Therefore, they should play an important role in determining the observable characteristics of DLA systems. In Paper I we found that the above prescription of star formation with \((\tau_0^\alpha, \alpha) = (1.5 \text{ Gyr}, -2)\) successfully reproduces both the metallicity evolution and H i column density distributions of observed DLA systems (see Figs. 1 and 3 in Paper I). Thus, we adopt these values in this study. From the estimated SFR, the luminosities of galaxies are computed by using simple stellar populations given by Kodama & Arimoto (1997). We also include a supernova feedback process and the merging process of galaxies. Details are presented in Paper I.

Finally, we address DLA systems in our model. We simply assume that all DLA systems have gaseous disks that are face-on to an observer, because the inclination effect hardly affects the column density distributions (see Fig. 4 in Paper I). Here the radial distribution of the H i column density follows an exponential profile with an effective radius of a gaseous disk, \(r_c\). It is assumed to be \(r_c = r_0(1 + z)\), where \(r_0\) is a radius provided by the specific angular momentum conservation of cooling hot gas. We also assume that the dimensionless spin parameter has a lognormal distribution with the average 0.06 and the logarithmic
variance 0.6. The central column density $N_0$ is given by $N_0 = \frac{M_{\text{cold}}}{(2\pi \mu m_H r^2)}$, where $m_H$ is the mass of a hydrogen atom and $\mu$ (1.3) is the mean molecular weight. The size of a DLA system is defined by the radius, $R$, at which $N_{\text{H}} = 10^{20} \text{ cm}^{-2}$. For each system, we take the column density averaged over radius within $R$. The above definition of DLA systems is the same as in Paper I.

We assume that cold gas in DLA systems is neutral. This is justified as follows. The $\text{H} \, \text{i}$ column density of DLA systems exceeds about $10^{20} \text{ cm}^{-2}$, which means that the cold gas is optically thick. So the ionization fraction averaged over the whole disk should be very small even if the UV background radiation exists around DLA systems. Prochaska & Wolfe (1996) calculated the ionization fraction in DLA systems taking into account radiation transfer, assuming a UV background intensity corresponding to that at $z \sim 2-3$, which is probably higher than at $z \lesssim 1$. When a DLA system is a uniform gas layer with a number density $n = 0.1 \text{ cm}^{-3}$, which is similar to that of typical DLA systems in our model, they found the ionization fraction $x(=n_e/n) < 0.1$. It is also possible that far-UV radiation emitted from internal OB stars ionizes the hydrogen atoms in disks. Radio observations of ionized gas in our Galactic disk, however, have revealed that the mass ratio of $\text{H} \, \text{ii}$ to $\text{H} \, \text{i}$ gases is about 0.01 and that the filling factor of $\text{H} \, \text{i}$ gas is less than 0.1 (Osterbrock 1989). We consider that the ionization fraction in DLA systems should be smaller than that in our Galaxy because ionizing photons are expected to be less than in our Galaxy, inferred from smaller SFRs in DLA systems. This feature has been also confirmed by recent measurements of the Al $\text{iii}$ abundance in DLA systems (Vladilo et al. 2001). The Al $\text{iii}$ abundance is a good tracer for estimating the intensity of ionizing UV radiation because the production of Al $\text{iii}$ requires UV photons. Vladilo et al. (2001) concluded that cold gas in DLA systems is almost neutral from the observed

Fig. 1.—Fundamental properties of DLA galaxies at redshifts $0 \leq z \leq 1$. Error bars with the averages indicate 1σ errors. The squares represent observational data (Rao et al. 2003). $B$-band luminosities are plotted in figures, except for in two cases for which the luminosities are measured in $K$ band only. The data with an upper limit of the luminosity are the DLA system in quasar 3C 336’s field. More details are presented in Rao et al. (2003). Note that the number fraction is $\sim 0.98 \ (L \leq 0.1L^*)$ in panel g.
small abundance of Al \textsc{iii}. Therefore, it is reasonable to assume that cold gas in DLA systems is neutral.

3. DLA GALAXY PROPERTIES AT LOW REDSHIFT

As shown in Paper I, our model has a good ability to reproduce various properties not only of galaxies both at high and low redshifts, but of DLA systems, particularly the observed distributions in the H\textsc{i} column density and the metallicity evolution. Here we present various properties of DLA galaxies at redshift $0 \leq z \leq 1$. Recently, Rao et al. (2003) compiled observational data of 14 DLA systems, including newly identified ones, at $0 \leq z \leq 1$ and showed distributions of their properties (luminosities, neutral hydrogen column densities, impact parameters, and number distributions). Their conclusion is that low-luminosity dwarf galaxies with small impact parameters dominate their compiled sample. Below we compare statistical properties of DLA systems in our model with the observations. Note that in our calculation the total number of model DLA galaxies is very large, $\sim 8 \times 10^3$, and the covering comoving volume is $\sim 2 \times 10^9$ Mpc$^3$ at redshift $z = 0$; these are statistically large enough to investigate the DLA properties. Note also that when presenting averaged values over redshifts, the comoving volume element $dV/dz$ is taken into account.

Following the presentation of observational data by Rao et al. (2003), Figure 1 shows distributions of the properties of DLA galaxies around luminosities in the $B$ band relative to $L^*$ (which corresponds to $M_B = -20.9$ mag; Rao et al. 2003), neutral hydrogen column densities $N_{\text{H}}$, and radii $b$. Figure 1a shows the luminosity evolution from $z = 1$ to the present. We find that the average luminosities predicted by our model are broadly consistent with those of some DLA galaxies observed at low redshifts but that some of these are brighter than our results. As shown in Paper I, our model predicts that the average circular velocities of dark halos hosting DLA systems increases toward

![Central surface brightness $\mu$ in the B band of DLA galaxies as a function of (a) redshift, (b) luminosity, (c) column density, and (d) size. Error bars with the averages indicate 1 $\sigma$ errors.](image-url)
low redshift as merging proceeds and that the average reaches $V_{\text{circ}} \sim 90 \text{ km s}^{-1}$ at redshift $z = 0$ (see Fig. 8 in Paper I). The luminosities also increase gradually as star formation proceeds, and the average luminosity is $L \sim 2 \times 10^9 L_\odot \sim 0.05L^*$ at present (see Fig. 10 in Paper I), which is fainter than that of normal spiral galaxies, $\sim L^*$. Thus our model apparently predicts average luminosities of DLA galaxies lower than those of the observations, which include some $L_*$-galaxies (Fig. 1a), unless the relevant selection biases are taken into account, as discussed in next section.

In Figures 1b and 1c our results show that DLA galaxies typically have neutral hydrogen column densities $N_{\text{HI}} \sim 10^{20.6} \text{ cm}^{-2}$ and radii $b \sim 3 \text{ kpc}$ (see also Figs. 1i and 1j), and their evolution is very moderate at $z \leq 1$. In Figure 1c it appears that the mean sizes are generally smaller than the observations. Because the radial sizes in our calculation provide upper limits of the impact parameters, our model seems to underpredict the sizes of DLA systems. Figure 1d depicts the number fraction of DLA galaxies as a function of redshift. Our result shows that the number increases toward higher redshift. This matches the observational trend of the redshift distribution of absorption-line systems, $dN/dz$, i.e., that their number increases up to $z \sim 5$ (e.g., Storrie-Lombardi & Wolfe 2000; Prochaska & Herbert-Fort 2004). Note that the number of DLA galaxies in Figure 1d is not identical to $dN/dz$. The former is weighted by the comoving volume element $dv/dz$ and the latter by the cross section of DLA systems.

Figures 1e and 1f present the mean column density and impact parameter as a function of luminosity. DLA galaxies with lower luminosities tend to have smaller impact parameters, while mean column densities depend very weakly on the luminosities for $L/L^* \gtrsim 0.1$. Note that Figure 1f indicates that some bright galaxies have large sizes, with radii $b \gtrsim 10 \text{ kpc}$, while the mean is $\sim 3 \text{ kpc}$. Our result also suggests that DLA galaxies with large $b$ ($\gtrsim 20 \text{ kpc}$) should be identified as $L^*$ spirals. We thus emphasize that luminous galaxies ($\geq L^*$) give rise to DLA absorptions, although the number fraction is much lower than that of the dominant population ($L \lesssim 0.1L^*$). This is in agreement with the observational fact that DLA systems have a wide range of morphology, from dwarf galaxies to bright spirals.

We also show how the extent of neutral gas around DLA galaxies scales with the column densities in Figure 1h. The relation between $b$ and $N_{\text{HI}}$ suggests that most of DLA systems have impact parameters smaller than 10 kpc. This figure also shows a trend that DLA galaxies with large $N_{\text{HI}}$ have small sizes, similar to the observation. Our model, however, seems to underpredict the size, as shown in Figure 1c. The reason for this is discussed in next section.

The above results suggest that DLA systems mainly comprise dwarf galaxies with small sizes. This is consistent with some trends emerging in the observations (Rao et al. 2003). Nevertheless, some observational data show that DLA galaxies are likely to be brighter and to be observed at impact parameters larger than our results, although the available observational sample is still small. These differences might be alleviated if some selection biases exist such that bright galaxies would likely be observed with large impact parameters; in other words, most of optical counterparts of DLA systems are hard to identify because of their faintness. In general, the identification of DLA galaxies among a large number of the candidates requires both photometric images and spectroscopic follow-ups. It is often extremely difficult to pick out the candidates and/or to identify them accurately. This is partly because they have low surface brightness and partly because the candidates exist in close proximity to a quasar line of sight. Below we investigate how such selection biases affect the distributions of the DLA galaxy properties discussed here.

4. SELECTION BIAS

4.1. Surface Brightness Limit

First, we focus on surface brightness distributions of DLA galaxies at redshift $0 \leq z \leq 1$ because detection limits are usually determined by a surface brightness. Figure 2 shows the $B$-band central surface brightness $\mu$ of DLA galaxies. Figure 2a depicts the evolution of their mean surface brightness. We find that the surface brightness becomes fainter toward higher redshift and that the mean surface brightnesses are $\sim 22 \text{ mag arcsec}^{-2}$ at $z \sim 0$ and $\sim 27 \text{ mag arcsec}^{-2}$ at $z \sim 1$. The evolution of surface brightnesses arises from both the luminosity evolution and cosmological dimming.

We also show distributions of central surface brightness averaged over $0 \leq z \leq 1$ weighted by the comoving volume element against luminosities, column densities, and sizes (in Figs. 2b–2d, respectively). Our results suggest that the surface brightness does not depend on the luminosity (for $L/L^* \gtrsim 0.1$) and the radius, but on the column density.

Figure 3 shows the number fractions as a function of $\mu$ at redshifts $z = 0$, 0.5, and 1. These results clearly show that DLA galaxies become brighter toward lower redshift and the mean central surface brightness increases by about 5 mag from $z = 1$ to 0. We also find the average surface brightness $\mu \sim 25 \text{ mag arcsec}^{-2}$ at $0 \leq z \leq 1$.

We do not expect that the very low surface brightness DLA galaxies computed here will be detected, because their faintness is below the detection limit. Although the limit depends on the quasar fields, Rao et al. (2003), for example, set their $3 \sigma$ limiting surface brightnesses at around $25 \text{ mag arcsec}^{-2}$ (their Table 2). According to the surface brightness limit, we pick out DLA systems with $\mu \leq 25 \text{ mag arcsec}^{-2}$ and show distributions of their...
properties in Figure 4, in which the number fractions shown in
bottom panels are defined as the ratios the number of DLA gal-
axies per bin to that of DLA galaxies that fulfill the selection
criteria. Our results show that most distributions are very similar
to those without the limit shown in Figure 1, while the mean
$N_{\text{HI}}$ becomes larger, particularly at high redshift ($z \sim 1$), and the
number fraction in $N_{\text{HI}}$ (Fig. 4) shows that DLA galaxies
apparently decrease when $N_{\text{HI}} \gtrsim 10^{21}$ cm$^{-2}$. These tendencies
occur for the following reasons. In Figure 2 we found that high
surface brightness galaxies have gaseous disks with high $N_{\text{HI}}$. In
other words, the surface brightness is strongly correlated with the
column density. At high redshifts, the LSB galaxies dominate
the population of DLA systems. Therefore, picking out only the
high surface brightness systems causes an increase in the mean
column densities at high redshifts. In contrast, the surface bright-
ness is not significantly correlated with the luminosity and the
size. This causes the distributions of $L$ and $b$ to remain similar
to those without the surface brightness limit. Therefore, we find
that this selection effect does not account for the observed dis-
tributions of DLA galaxy properties when the limit is as low as
$\mu \sim 25$ mag arcsec$^{-2}$.

4.2. Angular Size Limit

Second, we focus on a selection effect caused by the angular
sizes of DLA galaxies. Identification of a DLA galaxy requires
accurate determination of its redshift, which must be identical
to that of the possible DLA system counterpart. If a DLA galaxy
is compact and/or very close to a quasar line of sight, it often
happens that the image is blended or hidden in the point-spread
function (PSF) of the background quasar. Even after subtracting
the PSF from the blended image, noisy residuals often remain, so
no information can be extracted from within the radius of the
circle enclosed by the PSF. If a galaxy that gives rise to DLA
absorption is small and comparable to the size of the PSF, it is

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{Fundamental properties of DLA galaxies at redshifts $0 \leq z \leq 1$ if the central surface brightness $\mu < 25$ mag arcsec$^{-2}$. Error bars with averages indicate 1 $\sigma$ errors. The squares represent observational data (Rao et al. 2003). The number fractions in panels $d$, $g$, $i$, and $j$ are defined as the ratios the number of DLA galaxies per bin to that of DLA galaxies that fulfill the selection criteria. Note that the number fraction is $\sim 0.94 (L \leq 0.1L^*)$ in panel $g$.}
\end{figure}
more likely to cause this difficulty because the DLA galaxy is contaminated or hidden by the PSF. Even when the size is $\sim 1''$, it corresponds to the scale at most $\sim 6$ kpc at $z = 0.5$ and $\sim 8$ kpc at $z = 1$ in the cosmological model adopted here. This selection effect, which is called the “masking effect” hereafter, can be serious, because DLA galaxies are expected to be very compact, about 3 kpc on average in our model.

Figure 5 presents the distributions of DLA galaxies as a function of the angular radius $\theta$ at $z = 0.1$ (dotted line), 0.5 (dashed line), and 1 (solid line), respectively. The number fraction in large $\theta$ decreases toward high redshift, while the physical size of DLA galaxies apparently shows no evolution (see Fig. 1c). Thus, an evolution of the number distribution with redshift should be caused just by varying the distance, which directly affects the angular size.

In our model, 60%–90% of DLA systems have small angular sizes ($< 1''$). The limits of the angular sizes caused by the PSF are usually different from observed image to image. In most observations, however, the limiting angular sizes are likely to be larger than 1''. Here we set the angular size limit as $\theta_{th} = 1''$ and assume that DLA systems with angular sizes smaller than 1'' are not precisely resolved or identified as DLA galaxies because of the masking effect.

Taking into account this selection bias and the surface brightness limit ($\mu_{th} = 25$ mag arcsec$^{-2}$), we calculate the distributions of DLA galaxies with angular sizes larger than 1''. The results are presented in Figure 6. We find that at high redshifts DLA systems with large sizes mainly contribute to optically observable DLA galaxies, whereas the physical size corresponding to $\theta = 1''$ increases toward high redshifts. This is confirmed by the result for the evolution of their sizes in Figure 6c, in which the averages are larger than those in Figure 1c at $z \gtrsim 0.5$. Figure 6c suggests that DLA galaxies with large radii, $\sim 10$ kpc, obviously increase at redshift $z \gtrsim 0.5$ because of the masking effect (see Fig. 1c). It also appears that the number fraction of large-$b$ systems averaged over $0 \leq z \leq 1$ increases, as shown when Figure 6j is compared with Figure 1j. The masking effect evidently causes better agreement with the observational data of the impact parameters, particularly for large $b$ (Figs. 6c and 6h). Figure 6a shows that this bias also affects the apparent evolution of the luminosity of observed DLA galaxies. The luminosities agree better with the observations in Figure 6a by taking into account the masking effect. This is because most of large DLA systems, which are dominant at high redshift, are bright, as shown in Figure 6f. Figure 6d shows that the redshift distribution of DLA galaxies exhibits a trend similar to that in Figure 1d for a model without the selection effects, while the number evolution becomes milder.

Figure 6 is one of the main results of this study; that is, it shows that the selection biases, particularly the masking effect, are very important when we interpret the observed results of DLA galaxies, and that the biases lead to much better agreement with the observations. This suggests that bright DLA galaxies are not representative of the entire population of galaxies that produce DLA absorptions because the masking effect makes it difficult to identify faint and small galaxies as DLA galaxies.

To evaluate the masking effect on the luminosity more precisely, we vary the limit of angular size $\theta_{th}$, Figure 7 shows the results for $\theta_{th} = 1''$, 2'', and 3'', respectively. The large $\theta_{th}$ produces better agreement with the luminous DLA galaxies. Because the large $\theta_{th}$ causes faint galaxies not to be identified as DLA galaxies statistically, our results show that the average luminosity increases and matches better with the observations.

We have shown that the masking effect should be taken seriously in the identification of DLA galaxies at high redshift, although the limits depend on quasar fields. Our model also predicts that the rate of DLA galaxies missed because of the masking effect becomes 60%–90% in observations if the observable angular size is as small as 1'' and if compact galaxies, $\lesssim 3$ kpc, contribute significantly to the population of DLA systems.

5. Predicted Properties and Implications

5.1. Some Properties Expected by Radio Observations

Here we explore a way to study DLA galaxies that avoids the selection biases. Are there any methods to identify galaxies that produce DLA absorptions without the masking effect? It is expected that radio surveys can detect this kind of galaxy at low redshift if they have H$\alpha$ column densities as large as those measured in DLA systems. We focus on the H$\alpha$ mass in DLA systems, which correlates with observational properties in radio observations. The cross section of radio sources also provides a useful clue to studying the distribution of H$\alpha$ gas in the gaseous disk. First, a relation between the H$\alpha$ masses and sizes in DLA systems is plotted as a solid line with 1σ error bars in Figure 8a. We find that the logarithmic cross section, log $\sigma$, is linearly proportional to the logarithmic H$\alpha$ mass, log $M_{HI}$; i.e., $\sigma \propto M_{HI}^{1.0}$. The relation is fitted by averaged least-squares, and we find that slope $\alpha$ is $0.97 \pm 0.01$ for H$\alpha$ mass in the range $10^{6.5} \leq M_{HI}/M_\odot \leq 10^{10.5}$.

Recently, Rosenberg & Schneider (2003) observed local H$\alpha$–rich galaxies identified by a blind 21 cm survey: the Arecibo Dual-Beam Survey (ADBS). The ADBS sample consists of approximately 260 galaxies. They focused on the H$\alpha$–selected galaxies that have H$\alpha$ column densities comparable to those in DLA systems. If a bright quasar exists behind them, such H$\alpha$–selected galaxies should give rise to DLA absorption in the quasar spectrum. Including other data provided by different observations, they found a correlation between the cross section and the H$\alpha$ mass such that log $\sigma \propto M_{HI}^{1.2}$. The range of the observational data spreads within the dashed box region presented in Figure 8a, which spans a wide range of masses, $10^{6.5} \leq M_{HI}/M_\odot \leq 10^{10.5}$. The slope of the relation is estimated as 1.004 ± 0.021 in the
We find that this slope is entirely consistent with our results. The predicted cross sections are also within the range of the observational data. One might consider that the observed cross sections are somewhat larger than our results. The blind 21 cm emission-line survey has typical resolutions, $\sim 10^5$–$60''$, that are lower than those in photometric surveys. Such low resolutions may systematically lead to overestimates in the sizes of small galaxies.

We also show the averaged cross section of DLA systems at $0 < z < 1$ as a dotted line. The slope is almost identical with that of the relation at $z = 0$ (solid line), because both the cross sections and the HI masses are almost constant across redshift (see Figs. 1c and 7 in Paper I). We thus predict that the relation at high redshifts would be almost identical to that at $z = 0$. Figure 8b shows the number fraction in HI mass. As already discussed in Paper I, we find that the average HI mass is about $10^9 M_\odot$ at $0 < z < 1$ in our model. This result agrees the observational feature that DLA galaxies are dominated by those with HI masses near $10^9 M_\odot$ (Rosenberg & Schneider 2003).

We put emphasis on the facts, first, that there is a tight relation between the HI mass and the cross section in our model, similar to in the radio observations, and second, that our results are consistent with the properties obtained by radio observations in the whole observed range of HI mass. We will discuss the properties of the HI-selected galaxies extensively in a separate paper.

5.2. Star Formation Rates

SFRs provide an important clue to understanding DLA galaxies. Figure 9 presents the number fractions as a function of both SFR and SFR per unit area in DLA galaxies at $z = 0$ and 1, respectively. The SFR per unit area is simply estimated as the SFR divided by the disk area. All galaxies are simply assumed to be face-on to us when the area is computed, because the effects of the inclination are negligible (see Fig. 4 in Paper I). We here
discard spheroidal galaxies because they have much less H I gas than spirals and thus much lower SFRs. This assumption is suitable for calculating the SFR per unit area.

In Figure 9a we find that DLA galaxies have SFRs that range widely from 10⁻⁶ to 10² M⊙ yr⁻¹. At z = 1, the distribution of the SFRs has a large variance and a long tail toward low SFRs ≤ 10⁻² M⊙ yr⁻¹, while the variance at z = 0 is smaller than that at z = 1. Because less massive galaxies become dominant at high redshift (Fig. 8 in Paper I), and because their star formation has long timescales, galaxies with low SFRs increase toward high redshift. We also find that the mean SFR is ∼10⁻² M⊙ yr⁻¹ at 0 ≤ z ≤ 1. In Figure 9b the distributions of SFRs per unit area at z = 0 and 1 are quite similar to each other, with a mean value of ∼10⁻² M⊙ yr⁻¹ kpc⁻².

Figure 10 shows various distributions of SFRs. We plot the correlations of SFRs with redshift, luminosity, H I column density, size, and surface brightness. Figure 10a shows the redshift evolution of the SFRs. This indicates that the SFRs of DLA systems are ∼10⁻² M⊙ yr⁻¹ at z = 0–1 and that the evolution is quite moderate, similar to the stellar mass evolution (see Fig. 7 in Paper I). It appears that the variances of SFRs decrease toward low redshift, as also shown in Figure 9a. Figure 10b depicts the relation between SFRs and luminosities. Clearly, brighter galaxies have higher SFRs. For example, DLA galaxies brighter than L/L∗ ∼ 0.5 have SFRs larger than ∼10 M⊙ yr⁻¹, while the mean SFR is much lower, ∼10⁻² M⊙ yr⁻¹. It is also noticeable that DLA systems with high N_H I, large b, and high (small value of) μ have larger SFRs in Figures 10c, 10d, and 10e.

Consequently, our results imply that DLA galaxies have a wide range of SFR values. In observational studies, the SFRs in various types of galaxies have been derived and discussed by various authors. Measurements of SFRs give the most likely value of ∼3 M⊙ yr⁻¹ for our Galaxy (Cox 2000). Petrosian et al. (1997) reported that SFRs of local blue compact galaxies are ∼0.3–0.5 M⊙ yr⁻¹. SFRs of LSB galaxies estimated by van den Hoek et al. (2000) are about 0.03–0.2 M⊙ yr⁻¹, which is an empirical relation between Hα and I-band surface brightnesses in galactic disks. For dwarf and LSB galaxies, van Zee (2001) compiled their observational characteristics and estimated the SFRs using optical images in UBV and Hα passbands. The SFRs widely span at least 4 orders of magnitude, ∼10⁻⁵ to 10⁻¹ M⊙ yr⁻¹. The wide-range of SFRs is broadly consistent with those predicted by our model. In this sample, the galaxies have central surface brightnesses of between 20.5 and 25 mag arcsec⁻² and scale lengths of the disk from about 0.2 to 4.3 kpc. These properties are quite similar to those of DLA systems at z ∼ 0 in our model. Bowen et al. (2001) found a nearby DLA galaxy (SBS 1543+593) at z = 0.009 from photometric images obtained by a ground-based telescope and the Hubble Space Telescope (HST). Because this DLA system is the closest to us, it is expected to provide some clues to revealing the various properties of DLA galaxies. Recently, Schulte-Ladbeck et al. (2004) reported a more detailed study of this galaxy and found that it has properties typical of LSB galaxies: a central surface brightness of μ_v(0) = 22.8 ± 0.3 mag arcsec⁻² and SFR ∼ 0.006 M⊙ yr⁻¹. These properties also agree with those in our model. Together with these observational facts, our result leads to the conclusion that DLA systems mainly comprise dwarf galaxies in which the SFRs are low comparable to those in LSB galaxies.
If DLA galaxies are faint and compact, then most of the stellar counterparts cannot be detected by selection effects, which would prevent us from estimating the SFRs accurately by using emission lines. Absorption lines potentially provide us useful information on SFRs even if DLA galaxies are faint and compact. Recently, Wolfe et al. (2003a, 2003b) successfully estimated the SFRs per unit area of about 30 galaxies at \( z \approx 2 \) by means of a new method that uses the C ii/\( \lambda 1335.7 \) absorption line. They inferred the SFRs per unit area from the heating rate by far-UV radiation from massive stars under the assumption that the heating rate is equal to the rate of cooling by C ii/\( \lambda 1335.7 \) line emission.

Generally, the cold gas consists of two-phase media comprising a cold neutral medium (CNM) and a warm neutral medium (WNM). These media can stably exist in pressure equilibrium under some conditions, which are determined by a thermal balance of the two phases (e.g., McKee & Ostriker 1977; Wolfire et al. 1995). For example, Wolfire et al. (1995) investigated the stable condition of the CNM and the WNM in the interstellar medium (ISM). They found that neutral gas exists in two stable phases (1): a CNM with a typical temperature of \( T \approx 10^2 \) K and a typical number density \( n \approx 0.1 \) cm\(^{-3}\), and (2) a WNM with \( T \approx 8000 \) K and \( n \approx 10 \) cm\(^{-3}\). Wolfe et al. (2003a) showed stable conditions of the CNM and the WNM in DLA systems similar to those in the ISM of the Milky Way. At the present stage of our model, for simplicity we assume that the disk gas is a uniform one-phase medium. When the disk gas is uniformly distributed throughout plane-parallel disks with radius \( r \approx 3 \) kpc and scale-height \( h \approx 0.1 \) kpc, the typical number density is \( n \approx 6.1(N_{\text{H} I}/10^{20.5} \text{ cm}^{-2})(h/0.1 \text{ kpc})^{-1} \text{ cm}^{-3} \). In a low-density medium \( (n \approx 0.1 \text{ cm}^{-3}) \), cosmic rays are a dominant source of heating and ionization (Wolfe et al. 2003a). Assuming that the ionization rate by cosmic rays is proportional to the SFR, the ionization fraction depends on the SFR in addition to the number density and temperature. The physical conditions typically predicted by our model, \( N_{\text{H} I} \approx 10^{20.5} \text{ cm}^{-2} \), the SFR per unit area \( \approx 10^{-2.8} M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \), and \( n \approx 0.1 \text{ cm}^{-3} \) would result in the ionization fraction \( x_\text{f} = n_e/n < 0.1 \) (Wolfire et al. 1995, 2003a) and suggest that the disk gas in our calculation roughly corresponds to the WNM for two-phase model. Wolfe et al. (2003a) estimated the SFRs \( \approx 10^{-3} \) to \( 10^{-2} M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \) for DLA systems in the case that C ii absorption occurs in the CNM, and \( \approx 10^{-2} \) to \( 10^{-1} M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \) for DLA systems in case that C ii absorption occurs in the WNM. Interestingly, the former SFRs agree well with those in our model. This might imply that C ii

![Fig. 9](image-url)

Fig. 9.—(a) Number fractions of DLA galaxies as a function of SFR \( (M_\odot \text{ yr}^{-1}) \) at \( z = 0 \) (solid line) and \( z = 1 \) (dashed line). (b) Number fractions as a function of SFR per unit area \( (M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}) \) are also shown at \( z = 0 \) (solid line) and \( z = 1 \) (dashed line).

![Fig. 10](image-url)

Fig. 10.—SFRs of DLA galaxies as a function of (a) redshift, (b) absolute luminosity in B band, (c) H i column density, (d) size, and (e) surface brightness in the B band. Error bars with the averages indicate 1 \( \sigma \) errors.
absorption occurs in the CNM at \(z \gtrsim 2\) if the evolution of SFRs is moderate across redshift. It is also possible that the SFRs decrease toward low redshift (\(z < 2\)) in the WNM in which CN absorption arises. Indeed, since we assume that the gas is uniformly distributed in the disk, our modeling for disk gas has not reached the crucial stage at which we can compare our results with the estimated SFRs precisely. It would be valuable to investigate the evolution of multiphase structure in DLA systems in a subsequent study. Recent hydrodynamic simulations have estimated SFRs of DLA systems. For example, using smoothed particle, hydrodynamics simulation, Nagamine et al. (2004) found that simulated DLA systems have SFRs per unit area as low as \(\sim 10^{-3}\) to \(10^{-2}\) \(M_\odot\) yr\(^{-1}\) kpc\(^{-2}\). It is suggestive that their simulated SFRs are consistent with our results. We should note, however, that their simulation has several limitations, such as numerical resolutions, the narrow range of parameters relating to star formation and supernova feedback, and so on, and also that they predicted about an order of magnitude higher metallicities of DLA systems than observed values.

Figure 11 shows the SFR per unit area as a function of the \(\rm{H\,i}\) column density at redshift \(z = 0\) (solid line) and \(z = 1\) (long-dashed line) in comparison with the Kennicutt law (1998). The shaded area indicates the region of SFRs given by eq. (3), which includes systematic errors in the SFRs.

SFRs in DLA systems should be very moderate across redshift. SFR evolution at \(z > 1\) will be presented and discussed in a subsequent paper, including other fundamental properties, such as luminosities and sizes at high redshift.

5.3. Sizes and \(\rm{H\,i}\) Column Density Distributions of DLA Galaxies

Finally, we examine how the masking effect changes other properties of DLA galaxies. First, Figure 12 shows the radial size \(b\) as a function of \(B\)-band absolute magnitude brighter than \(M_B \sim -17\) mag. Our result shows a trend that bright DLA galaxies are likely to be observed with large impact parameters. The mean radial size appears larger than the observational data because the radial size provides an upper limit for the impact parameters. This scaling relation is fitted by averaged least squares, \(b \propto M_B^\alpha\), and we find the slope \(\alpha = -0.18 \pm 0.02\) in the magnitude range \(-21\) mag \(\leq M_B \leq -16.5\) mag. Taking into account the masking effect, we also show the \(b-M_B\) relation as a dashed line in this figure. It is also evident that the masking effect with \(\theta_b = 1\)—hardly changes the slope for bright galaxies, because the masking effect only reduces the number of compact and faint galaxies. Recently, Chen & Lanzetta (2003) observationally found a scaling relation between the \(\rm{H\,i}\) disk size \(R\) and the \(B\)-band luminosity \(L_B\) of DLA galaxies, \(R \propto L_B^\beta\) with \(\beta = 0.26 \pm 0.24\). This relation is plotted as the dotted line in Figure 12. We find that the scaling relation is consistent with our predicted one within \(1\) \(\sigma\) scatters. For example, our relation has the indices \(\beta = 0.35 \pm 0.02\) and \(0.45 \pm 0.01\) with and without the masking effect, respectively. Thus the tight relationship between the radial size and the magnitude found in our model, which suggests that brighter galaxies are larger, is consistent with the observations.

Second, we calculate a neutral hydrogen column density distribution of DLA galaxies taking into account the masking effect. Figure 13 shows the column density distribution at \(z = 1\). The
data points are taken from Storrie-Lombardi & Wolfe (2000).¹ We also take additional data reported by Rao & Turnshek (2000), which include a sample at low redshift \( z \approx 0.8 \). In Paper I (Figs. 3 and 5) we reproduced the column density distribution of DLA systems, especially for low-redshift ones. In Figure 13 the solid and dashed lines indicate the distributions of DLA galaxies with and without the masking effect, respectively. The masking effect is the most significant at \( z = 1 \), because the angular size of a constant physical size approaches a minimum at around \( z = 1 \). Therefore, this effect reduces the number of DLA galaxies over the whole range of column densities. We find that even if \( \theta_H = 1'' \), the column density distributions are still consistent with the observational data (Fig. 13, dashed line). We thus predict that optically selected DLA galaxies also have a column density distribution similar to that of all DLA absorbers even if the selection effect exists.

6. CONCLUSIONS AND DISCUSSION

We have investigated DLA absorbing galaxies at redshifts \( 0 \leq z \leq 1 \) in the hierarchical structure formation scenario using a semianalytic galaxy formation model. In the previous study (Okoshi et al. 2004), we found that our model can reproduce many fundamental properties of DLA systems, such as the metallicity evolution, the column density distribution, and the mass density of cold gas, in addition to those of local galaxies (Nagashima et al. 2001). In this paper we have focused our attention on their host galaxies, which give rise to DLA absorption at \( 0 \leq z \leq 1 \), and used the model to calculate the observable properties. The main conclusions are the following:

1. Most of DLA galaxies producing DLA absorption lines in quasar spectra are faint and compact. Their typical size is \( \sim 3 \) kpc, and the mean surface brightnesses are \( \sim 22 \) mag arcsec\(^{-2} \) at \( z \approx 0 \) and \( \sim 27 \) mag arcsec\(^{-2} \) at \( z \approx 1 \). Some selection biases are required for those to have fundamental properties consistent with those of DLA galaxies observed in optical and near-infrared images (Rao et al. 2003).

2. Two selection biases were studied here. The first is a bias caused by LSB galaxies. A typical limit of surface brightness in observations, \( \mu_{H_1} = 25 \) mag arcsec\(^{-2} \), has a negligible effect. The second is the masking effect, as a result of which only large DLA galaxies are detectable because small ones must reside in close proximity to a quasar line of sight, where the quasar PSF dominates. Considering a typical masking angular size \( \theta_H = 1'' \), this effect is significant and makes the distributions of fundamental properties of DLA galaxies agree much better with the observations.

3. The rate of DLA galaxies missed because of the masking effect reaches 60%–90% if low-luminosity galaxies with small impact parameters \( \sim 3 \) kpc) significantly contribute to the population of DLA systems.

4. A tight relation between the \( H_1 \) mass and the cross section was confirmed in DLA systems. We also found that \( H_1 \)–rich galaxies with \( 10^9 M_\odot \) mainly contribute to the population of DLA systems at \( z \approx 0 \). These results are entirely consistent with the properties of \( H_1 \)–selected galaxies in a radio survey (the ADBS; Rosenberg & Schneider 2003). Investigations by such blind radio surveys could provide alternative possibilities for exploring DLA galaxies without the selection biases found in photometric surveys.

5. DLA galaxies display a wide range in SFRs, with the mean about \( 10^{-2} M_\odot \) yr\(^{-1} \). This suggests that DLA galaxies consist of dwarf galaxies in which SFRs are low, comparable to those in LSB galaxies.

Although more data would be required to confirm these conclusions, this study suggests that most DLA systems are LSB dwarf galaxies, although some are massive spiral galaxies.

Previous attempts have been made to detect DLA galaxies much closer to background quasars, to unveil the nature of DLA systems. Steidel et al. (1997) studied a DLA system at \( z = 0.656 \) from photometric images and spectroscopy of quasar 3C 336’s field. They concluded that there is no galaxy brighter than \( 0.05 L_\odot \) within \( 0.5 \), corresponding to a radius \( \sim 2 h^{-1} \) kpc, to the quasar line of sight. Bouché et al. (2001) tried to detect \( H_\alpha \) emission in the region behind the PSF of the same quasar, but they failed to detect any \( H_\alpha \) emitters in the vicinity of the line of sight of the quasar within a range of \( 0.24–30 h^{-1} \) kpc. In this observation, they reported that the \( 3 \) \( \sigma \) flux limit was \( \sim 3 \times 10^{-17} \) ergs s\(^{-1} \) cm\(^{-2} \) for an unresolved source. This corresponds to an SFR of \( 0.3 h^{-2} M_\odot \) yr\(^{-1} \). Our results show that the mean SFR at \( z \approx 0.65 \) is \( \sim 10^{-2} M_\odot \) yr\(^{-1} \), which is much lower than the SFR corresponding to the flux limit. Therefore, if LSB galaxies dominate the population of DLA systems, the low surface brightness, corresponding to the low SFR, may prevent us from detecting \( H_\alpha \) emission.

If a PSF size \( \theta_H \) is constant at \( z > 1 \), the physical size corresponding to \( \theta_H \) becomes smaller, so that the masking effect would be less serious than for the samples at redshifts \( z \leq 1 \). Kulkarni et al. (2000) reported that they were able to detect an \( H_\alpha \) emission feature from a DLA system at \( z = 1.892 \) at a projected separation of \( 0.25 \) from a line of sight toward the quasar LBQS 1210+1731, using HST NICMOS. They concluded that the size of the \( H_\alpha \) emitter would be \( 2–3 \) kpc if it is associated with the DLA system and the feature is not PSF artifact. Fynbo et al. (1999) and Møller et al. (2002, 2004) have successfully

¹ We adjust the data points for the cosmological model (LCDM) adopted here.
detected five DLA galaxies at $2 \leq z \leq 3$. They found that all Lyα emitters reside in very close proximity to background-quasar lines of sight and concluded that they have small impact parameters about 1–3 kpc. Although these are observational properties of high-redshift ($z > 2$) DLA galaxies, it is suggestive to recognize the fact that their conclusions are consistent with our results.

It may be more likely that DLA galaxies can be identified at $z \sim 0$ than high-redshift ones. This is partly because the physical size corresponding to a constant $\theta$ becomes small enough toward the present to identify compact galaxies around a quasar line of sight, and partly because the surface brightnesses of DLA galaxies are expected to be high enough that we can detect their photometric images. Like a DLA galaxy (SB1543+593) at $z = 0.009$ (Schulte-Ladbeck et al. 2004), DLA galaxies at $z \sim 0$ have the advantage that their detection is less affected by the masking effect and/or their faintness than high-redshift ones because they are close to us. Thus, we again emphasize our conclusion that the selection biases are very important to understanding the nature of DLA galaxies and to interpreting results of photometric observations.

Radio observations offer some possibilities for exploring the nature of H i-rich galaxies such as DLA systems. Some blind 21 cm surveys provide interesting information for establishing fundamental properties of local H i-selected galaxies such as the H i mass function, which is the distribution function of galaxies as a function of the H i mass, the relation between the H i mass and the near-IR luminosity of their counterparts, and so on.

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