H I gas in higher density regions of the intergalactic medium\textsuperscript{1}

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ABSTRACT

Using H I absorption alone, we attempt to separate H I absorption lines in quasar spectra into two categories; HDLs (Higher Density Lines) and LDLs (Lower Density Lines), and we discuss the difference in their physical properties. We deblend and fit all H I lines with Voigt profiles, and make an unbiased sample of H I lines covering a wide column density range ($12 < \log N_{HI} < 19 \text{ cm}^{-2}$). To reduce the influence of line blending, we simultaneously fit several Lyman series lines. As a result of a two-point correlation analysis, we found that higher column density H I lines are clustering at $\Delta v < 200 \text{ km s}^{-1}$, while lower ones at $\Delta v < 100 \text{ km s}^{-1}$. We define HDLs as H I lines with $15 < \log N_{HI} < 19 \text{ cm}^{-2}$ and all H I lines within $\pm 200 \text{ km s}^{-1}$ of a line with $\log N_{HI} > 15 \text{ cm}^{-2}$, and LDLs as others with $12 < \log N_{HI} < 15 \text{ cm}^{-2}$. We found that the HDLs have smaller minimum $b$-values for a given column density than the LDLs. This difference is successfully reproduced by our Hydrodynamic simulation. The LDLs seem to be cool or shock-heated diffuse IGM gas, while the HDLs are likely to be cooler dense gas near to galaxies.

Subject headings: quasars: absorption lines — galaxies: ISM — intergalactic medium

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1. Introduction

Quasars have been used as background sources, allowing the study of objects that lie between us and them, most of which make Ly$α$ absorption lines. To date, line-profile fitting analysis for Ly$α$ absorption lines has been carried out to study physical parameters such as the velocity width and the column density (Pettini et al. 1990; Carswell et al. 1991; Rauch et al. 1992; Hu et al. 1995 (H95 hereafter); Lu et al. 1996a (L96 hereafter); Kirkman & Tytler 1997 (KT97 hereafter)).

Samples of H i absorption lines usually contain (i) H i lines originating in the intergalactic diffuse gas, and (ii) H i lines produced near or in intervening galaxies. The former could be weak H i lines, widely distributed as the Ly$α$ forest (hereafter we call these “LDLs” or “Lower Density Lines”), whereas the latter are likely to be strong H i lines clustered as metal absorption lines (hereafter we call these “HDLs” or “Higher Density Lines”). HDLs are thought to be caused by discrete clouds. On the other hand, LDLs are probably arising from photoionized IGMs in the continuous density fields that are broadened by Hubble flow (e.g., Rauch 1998; Kim et al. 2002). Here, the reader can think of density as column density $N_{HI}$, or volume density, since numerical simulations show that the two are correlated (Zhang et al. 1998). The HDLs are lines formed in or near to higher density parts of the IGM. As the log $N_{HI}$ increases, especially above about 17, these regions are more likely to be in or near the outer parts of galaxies, or clumps that will become galaxies. In contrast, the LDLs arise in relatively lower density regions of the IGM.

There are studies which suggest that some H i absorption lines have a close relationship with galaxies near the line of sight, not only on small scales at low-z (Grogin & Geller 1998; Penton, Stocke, & Shull 2002) but also on large scales at high-z (Adelberger et al. 2003). McDonald, Miralda-Escudé, & Cen (2002) presented theoretical predictions of the correlation between the Ly$α$ forest transmitted flux and the mass of absorbers within $\sim 5h^{-1}$ Mpc (comoving) of the line of sight. Other spectroscopic and imaging observations have been carried out in order to study the statistical relationship between the Ly$α$ absorbers and galaxies at low-z. The most important result is that the Ly$α$ equivalent widths are anti-correlated with the projected distance of the nearest galaxies within 500$h^{-1}$ kpc of the galaxies (Lanzetta et al. 1995; Tripp, Lu, & Savage 1998; Davé et al. 1999; Chen et al. 2001). Thus, some H i absorbers seems to be closely related with galaxies.

Thus, the analysis of HDLs and LDLs is indispensable for the detailed investigation of physical properties of H i gas. However, one of the most serious problems in such an analysis is that the Ly$α$ absorption lines are so heavily blended with each other that it is difficult to separate and fit them individually. This problem is often seen in strong H i lines with log $N_{HI}$ > 15 cm$^{-2}$.

In some past studies, the column densities of strong H i lines have been evaluated using the Lyman limit optical depth for LLSs, or the total rest-frame equivalent width for DLA systems without fitting them by Voigt profiles (e.g. Lanzetta et al. 1991; Petitjean et al. 1993). These methods, however, evaluate only the total column densities and Doppler parameters of the heavily blended H i lines.
In this study, we attempt to fit all H i lines with Voigt profiles, construct an unbiased sample of H i lines over a wide column density range (12 < log $N_{HI}$ < 19 cm$^{-2}$), and investigate their physical parameters, such as column density, Doppler parameter, and clustering properties. In order to separate the heavily blended (strong) H i lines and fit them individually with Voigt profiles, we use not only the Ly$\alpha$ line but also higher Lyman series lines, such as Ly$\beta$ and Ly$\gamma$, to improve the fitting accuracy.

This method has previously been applied to only a several LLS and DLA systems (e.g. Songaila et al. 1994; Tytler, Fan, & Burles 1996; Wampler, Baldwin, & Carswell 1996; Carswell et al. 1996; Songaila, Wampler, & Cowie, 1997; Burles & Tytler 1998a,1998b, Burles, Kirkman, & Tytler 1999; Kirkman et al. 2000; O’Meara et al. 2001; Kirkman et al. 2003) and the Ly$\alpha$ forest in two quasar spectra (Kim et al. 2002). Here we apply this fitting method to 40 quasar spectra acquired with KECK + HIRES (Vogt et al. 1994).

Finally, we attempt to separate H i lines into HDLs and LDLs, and apply our statistical analysis to these two classes separately. We confirm that the column density distribution and the Doppler parameter distribution of LDLs are similar to the past results (H95; L96; KT97). We found the most remarkable difference between HDLs and LDLs in the plot of column density vs. Doppler parameter, which suggests that H i absorbers are not produced by a single phase (or a single population). This difference is also reproduced by our Hydrodynamic simulation. The summary of the other results and the detailed description of each absorption system are presented in Misawa et al. (2004).

We give a brief description of the observation in § 2. In § 3, we explain how to evaluate the line parameters. In § 4, we investigate the physical properties of HDLs and LDLs, and compare the observational results with the Hydrodynamic simulation. We summarize our results in § 5.

2. Observations

The sample quasars were originally selected from a survey taken for measurements of the D/H (deuterium to hydrogen) abundance ratio. The typical ratio of D/H is so small, 3 ×10$^{-5}$ (Kirkman et al. 2003 and references therein), that we can only detect D i lines corresponding to H i lines with large column densities, log $N_{HI}$ ≥ 16.5 cm$^{-2}$. Given this fact, we observed quasars in which either DLA systems or LLSs were detected. Here we examine KECK+HIRES spectra of 40 quasars. We used a 1′′.14 slit which provided a resolution of 8.0 km s$^{-1}$. The spectra were extracted by the automated program, MAKEE package, written by Tom Barlow.
3. Preparation of uniform sample

Instead of detecting all the H\textsc{i} lines in the spectra of the 40 quasars, this study includes only the H\textsc{i} lines with log $N_{\text{HI}} > 15$ cm$^{-2}$, and all other H\textsc{i} lines within $\pm 1000$ km s$^{-1}$ of such H\textsc{i} lines. The reason is described below.

3.1. Detection of H\textsc{i} systems

We at first searched for H\textsc{i} lines with log $N_{\text{HI}} > 15$ cm$^{-2}$, in the following way: (1) we found H\textsc{i} lines already discovered in DLA systems or LLSs in earlier work (Sargent, Steidel, & Boksenberg 1989; Lanzetta 1991; Tytler 1982; Burles 1997), (2) we checked for H\textsc{i} lines corresponding to previously discovered metal absorption systems (Péroux et al. 2001; Storrie-Lombardi et al. 1996; Petitjean, Rauch, & Carswell 1994; Lu et al. 1993; Steidel & Sargent 1992; Lanzetta et al. 1991; Barthel, Tytler, & Thomson 1990; Steidel 1990; Sargent et al. 1988), and (3) we finally attempted to detect H\textsc{i} lines ourselves that satisfied both of the following conditions — (i) the H\textsc{i} line has a column density of log $N_{\text{HI}} \geq 15$ cm$^{-2}$, and (ii) at least one higher Lyman series, e.g. Ly$\beta$ and Ly$\gamma$ lines, is present along with Ly$\alpha$ in the observed wavelength range, which improves the reliability of line fitting. We do not consider metal lines.

Metal absorption lines (Sargent et al. 1980; Young, Sargent, & Boksenberg 1982; Sargent, Steidel, & Boksenberg 1988; Petitjean & Bergeron 1994; Churchill & Vogt 2001; Pichon et al. 2003) including those in DLA systems (Lu et al. 1996b) cluster over $\Delta v < 400$ km s$^{-1}$. It is then sufficient to detect all lines within $\pm 1000$ km s$^{-1}$ of the H\textsc{i} lines with log $N_{\text{HI}} > 15$ cm$^{-2}$ for the purpose of studying the physical properties of weak and strong H\textsc{i} lines. Where more than one H\textsc{i} line with log $N_{\text{HI}} > 15$ cm$^{-2}$ was detected within this velocity window, the position of the line with the largest column density (hereafter the “main H\textsc{i} component”) was considered to be the center of the H\textsc{i} system. As an example, we show the velocity distribution of H\textsc{i} lines for the system at $z_{\text{abs}} = 3.321$ in the spectrum of Q0014+8118 in Figure 1 (see also Burles, Kirkman, & Tytler 1999). With this method, we detected 86 H\textsc{i} systems at $2.1 < z < 4.0$ in the spectra of 31 quasars, out of a total of 40 examined.

3.2. Evaluation of Line Parameter

For the fitting of each absorption line with a Voigt profile, we fit all the accessible lines in the Lyman series, helping us deblend H\textsc{i} lines and make an unbiased sample of H\textsc{i} lines.

In the process of line detection, we removed very narrow lines with Doppler parameter of $b < 4.81$ km s$^{-1}$ or FWHM $\sim 8.0$ km s$^{-1}$, which is the resolution of our spectra. We decided to ignore all lines with $b < 15$ km s$^{-1}$ as described later. If the Voigt fitting allowed different solutions during the fitting trials, the result with the minimum number of lines was chosen. This occurs
mainly in the saturated region for which we have only small number of Lyman series information. If we fit the line profiles using smaller number of components than the actual number, the $b$-values could be overestimated. On the other hand, the column density cannot be easily overestimated, because only a small rise of the column density significantly changes the line profiles (e.g., damping profile) especially at the saturated regions.

Once the fitting model was applied to the absorption lines in some region of the spectra, we used $\chi^2$ minimization to find the model parameters which best fitted the observed spectrum. The formal errors on the fitted parameters for lines with $b < 30$ km s$^{-1}$ are $\sigma(\log N_{HI}) = 0.09$ cm$^{-2}$, $\sigma(b) = 2.1$ km s$^{-1}$ and $\sigma(z) = 2.5 \times 10^{-5}$. Before beginning our statistical analysis, we prepared an unbiased sample of H I lines, by eliminating inappropriate H I systems that have disadvantages described below.

(1) poor fitting due to gaps in echelle formatted spectra: Echelle- formatted spectra sometimes have data gaps between echelle orders. This occurs frequently in the redder part of the spectrum (e.g., $\lambda > 5000$ Å in our data). Spectral gaps appear every $\sim 100$ Å, and the widths of the wider gaps are no less than 20 Å depending on the wavelength. If the Lyman series line damaged by the spectral gaps is Ly$\alpha$, the fitting accuracy for the system is very low. Therefore we removed H I systems whose Ly$\alpha$ lines are affected by spectral gaps wider than 100 km s$^{-1}$.

(2) poor fitting due to strong DLA wings: DLA (and sub-DLA) systems with large H I column densities of $\log N_{HI} \geq 19$ cm$^{-2}$ are unsuitable for our study, not only because their absorption profiles are damped so strongly that almost all weak components are blanketed by the damping wings, but also because the spectra around DLA lines are not normalized correctly due to the strong absorption features.

(3) close proximity in redshift to the background quasars: The Ly$\alpha$ forest disappears in the regions redward of the Ly$\alpha$ emission lines of the quasars. Therefore we remove H I systems at a distance of $\leq 1000$ km s$^{-1}$ from the Ly$\alpha$ emission lines, because the asymmetrical distribution of their H I lines complicates the clustering analysis described in § 4.1.

(4) overlapping with other H I systems: H I system pairs, whose velocity windows of $\pm 1000$ km s$^{-1}$ are overlap, are also excluded, as their distribution of H I lines could affect each other and the line clustering analysis is contaminated.

Finally, we have an unbiased sample of 973 H I lines in 61 H I systems. However the sample is not homogeneous because the S/N ratio varies. The S/N ratios of the spectra are at least S/N $\simeq 11$ per 2.1 km s$^{-1}$ pixel and the mean value is S/N $\simeq 47$ for Ly$\alpha$ lines.
4. Physical properties of H I lines

We used the sample prepared in § 3, to study the H I line parameters. Our analysis is similar to that of previous studies (e.g. H95; L96; KT97), but with three key differences: (i) earlier studies used all H I lines detected in the quasar spectra, whereas we use only H I lines within ±1000 km s⁻¹ of the main components with log $N_{HI} > 15$ cm⁻², (ii) our sample contains a number of strong H I lines (log $N_{HI} > 15$ cm⁻²) in addition to weak lines (log $N_{HI} < 15$ cm⁻²), and (iii) our sample covers a wide redshift range, 2.0 ≤ $z$ ≤ 4.0, compared with those of the past studies, $\Delta z \sim 0.5$.

4.1. Clustering Properties

Our sample contains not only LDLs but also HDLs. Davé et al. (1999) noted in their hydrodynamic simulations that galaxies tend to lie near the dense regions that are responsible for strong H I lines. Therefore, we attempted to classify the lines using their clustering along the line of sight by constructing the two-point correlation function (Sargent et al. 1980),

$$\xi(v) = \frac{N(v)}{N_{exp}(v)} - 1,$$

where $N(v)$ is the number of observed pairs at a velocity separation of $v$, and $N_{exp}(v)$ is the number of line pairs expected if they are randomly placed along the line of sight. $N_{exp}(v)$ is calculated by Monte Carlo simulations. Webb (1987) found significant clustering, $\xi(v) = 0.32 \pm 0.08$ over the velocity range 50 < $v$ < 150 km s⁻¹ at $1.9 < z < 2.8$. H95 confirmed the same trend with $\xi(v) = 0.17 \pm 0.045$, over the same velocity range at $\langle z \rangle = 2.8$. With a large sample of H I lines with log $N_{HI} > 13.8$ cm⁻² at $1.7 < z < 4.0$, Cristiani et al. (1997) also found that the correlation function at $v \sim 100$ km s⁻¹ increases with log $N_{HI}$. On the other hand, Rauch et al. (1992), L96, and KT97 did not find any clustering for similar velocity ranges at $2.7 < z < 3.4$, $\langle z \rangle = 3.7$, and $\langle z \rangle = 2.7$, respectively.

In Figure 2, we show the number of H I lines of our sample at a given distance from the main components. The H I line with relatively large column densities tend to cluster around the main components, and have a symmetrical distribution, suggesting that they are related to each other. In contrast, the number of H I lines with smaller column densities decrease near the center of H I systems.

Therefore we calculated $\xi(v)$ for some subsamples, varying the column density ranges. At first, a number of artificial lines matching the number of observed lines were randomly inserted into the 61 H I system windows. Since the observed H I systems always have main components at $v = 0$ km s⁻¹, we also placed an artificial line at the center of each system in order to produce unbiased simulated data. This process was repeated 250 times to obtain an average value for $N_{exp}(v)$.

As a result of the analysis using all H I lines, we found that $\xi(v)$ shows a slight number excess at $\Delta v < 200$ km s⁻¹. The values of $\xi(v)$ for H I lines with various column density ranges in bins
with a spacing of 50 km s\(^{-1}\) at 50 < \(v\) < 200 km s\(^{-1}\) are summarized in Table 1. Column (1) is the range of column density, columns (2), (3), and (4) are the values of \(\xi(v)\) and 1\(\sigma\) Poisson errors for velocity separations of 50 – 100, 100 – 150, and 150 – 200 km s\(^{-1}\), respectively, and column (5) is the velocity width where the lower 1\(\sigma\) deviation of \(\xi(v)\) first goes below \(\xi(v) = 0\) over \(v > 50\) km s\(^{-1}\). Column (6) is the number of HI lines in each subsample. We see non-zero \(\xi(v)\) at velocity separations of \(v \sim 100\) km s\(^{-1}\) for weak HI lines, and \(v \sim 200\) km s\(^{-1}\) for strong HI lines. The correlation degree at \(v = 50 – 100\) km s\(^{-1}\) was found to have a maximum for HI lines with 15 < log \(N_{HI}\) < 19 cm\(^{-2}\). This is one reason why we chose to use log \(N_{HI}\) = 15 cm\(^{-2}\) as part of our definition of HDLs.

Within \(\sim 0.5h^{-1}\) comoving Mpc of Lyman Break Galaxies (LBGs), the IGM contains less neutral hydrogen gas compared with the cosmologically averaged value at \(z \sim 3\) (Adelberger et al. 2003). Some cosmological hydrodynamic simulations (e.g., Croft et al. 2002; Kollmeier et al. 2003) showed that this effect could be produced not by UV flux from the LBGs but by the galactic winds. This decreased absorption was detected in Adelberger et al. (2003) because the lines of sight to the quasars and the LBGs are different. In our spectra, strong HI lines (maybe produced in the intervening galaxies) absorb most of the quasar flux within 50 km s\(^{-1}\) of their centers, which prevents us from detecting HI deficit in the vicinity of the strong HI lines.

### 4.2. HDLs and LDLs

We classified HDLs and LDLs with the following procedure. At first, we regarded all HI lines with log \(N_{HI}\) > 15 cm\(^{-2}\) as HDLs, because the line clustering is stronger as log \(N_{HI}\) increases as Cristiani et al. (1997) found, and we found above. But we emphasize that the value of log \(N_{HI}\) = 15 cm\(^{-2}\) is not strict. These strong HI lines may also be accompanied by weak HI lines that are physically associated with them. In fact, metal absorption lines sometimes have a core-halo structure; the strongest line is at the center of the absorption system, while the weak lines exist almost symmetrically on both sides of the strong one (e.g. Lu et al. 1996b; Prochaska et al. 2001; Misawa et al. 2003). Therefore, we defined a velocity distribution width for HDLs, \(v_{HDL}\). Since HI lines with relatively large column densities of log \(N_{HI}\) = 13 – 19, 14 – 19, 15 – 19, and 16 – 19 cm\(^{-2}\) are correlated with each other within the velocity separation of \(v \sim 200\) km s\(^{-1}\), we adopted \(v_{HDL} = \pm 200\) km s\(^{-1}\), and regard all HI lines with 12 < log \(N_{HI}\) < 15 cm\(^{-2}\), within \(\pm 200\) km s\(^{-1}\) of HI lines with log \(N_{HI}\) > 15 cm\(^{-2}\) as HDLs. Hereafter we call the lines with log \(N_{HI}\) < 15, lying within 200 km s\(^{-1}\) of a log \(N_{HI}\) > 15 line, halo HDLs in distinction from the original HDLs. Finally all the 973 HI lines were separated into 306 HDLs (including halo HDLs) and 667 LDLs based on these criteria.
4.3. Column density – Doppler parameter relation

Using the subsamples of HDLs and LDLs, we investigated the correlation between the Doppler parameters and column densities. Our results are summarized in Figure 3.

In this figure, we also show lines with $5 < b < 15$ km s$^{-1}$. We find 62 LDLs and 16 HDLs with $12 < \log N_{HI} < 14$ cm$^{-2}$ and $5 < b < 15$ km s$^{-1}$, or 8% of the 973 LDLs + HDLs with $b > 15$ km s$^{-1}$ (16/62 = 25.8%) is similar to that for lines with $b > 15$ and the same column density range (142/583 = 24.4%). Since we did not identify metal lines, many of them could be metals, and since our spectra have a range of S/N, many could be erroneous. Past studies that did consider these two effects found very few H$\text{I}$ lines with these parameters (KT97; H95; L96). Hence, we ignore all lines with $b < 15$ km s$^{-1}$.

When we ignore H$\text{I}$ lines with $b < 15$ km s$^{-1}$, we found a positive correlation between the minimum Doppler parameter, $b_{\text{min}}$, and column density not only for LDLs approximately fitted by $b_{\text{min}} = 4.0 \times \log\left[\frac{N_{HI} \text{(cm}^{-2})}{10^{12.5}}\right] + 14.0$ km s$^{-1}$ at $12.5 < \log N_{HI} < 15.0$ cm$^{-2}$ as seen in the past papers (e.g. KT97), but also for HDLs fitted by $b_{\text{min}} = 1.3 \times \log\left[\frac{N_{HI} \text{(cm}^{-2})}{10^{12.5}}\right] + 10.5$ km s$^{-1}$ at $12.5 < \log N_{HI} < 19.0$ cm$^{-2}$. At $\log N_{HI} > 15$ cm$^{-2}$, the HDLs often have $b$ values below the extrapolation of eqn. (2) for the LDLs. We, however, cannot compare the $b_{\text{min}}$ values of LDLs with those of HDLs directly at $\log N_{HI} > 15$ cm$^{-2}$, because there are no LDLs at that region. Nonetheless, if we look at the region of $\log N_{HI} = 14 - 15$ cm$^{-2}$, a difference in the distribution of LDLs and HDLs is clear. At $\log N_{HI} = 14 - 15$, only 2% (2 of 91) LDLs are below the eqn. (2), while 20% (12 of 59) HDLs are located there. We do not think this difference is just a statistical accident. At $\log N_{HI} < 14$ cm$^{-2}$, we do not see any remarkable difference between them, which could mean that there is little difference between the physical properties of LDLs and halo HDLs.

4.4. Comparison with simulation

For weak H$\text{I}$ lines, the correlation between column density and minimum Doppler parameter has already been reproduced by CDM simulations. Zhang, Anninos, & Norman (1995) performed the hierarchical three-dimensional numerical simulation, and found the minimum $b$-value is increasing slightly with column density in a linear fashion. In order to mimic observational analysis more closely, Zhang et al. (1997) synthesized absorption spectra, and extracted, deblend, and fit the absorption features in generated spectra. The recovered data exhibit a $b_{\text{min}}$ dependence on the column density well fitted by $b_{\text{min}} = 5.5 \times \log[N(\text{cm}^{-2})/10^{12.5}] + 12.8$ km s$^{-1}$, which is consistent with the KT97’s and our results for LDLs (eqn. (2)) shown in Figure 3.
We have performed a three-dimensional hydrodynamical simulation of Lyα clouds in a CDM dominated universe, and compared it with our observational results. We used the following input parameters; $\Omega_b=0.04$, $\Omega_m=0.30$, $\Omega_{\Lambda}=0.70$, $H_0=70$ km s$^{-1}$ Mpc$^{-1}$, $\sigma_8=0.73$, and power spectrum slope $n = 1$. We chose the size of the computational box to be $L=0.7h^{-1}$ Mpc with the effective grid resolution of $256^3$. We used the Haardt & Madau (1996) quasar spectrum with the photo-ionization rate, $\gamma_{HI} = 5.6 \times 10^{-13} \times (1+z)^{0.43} \times \exp[-(z-2.3)^2/1.95]$ ionizations per H i atom per second in the optical thin limit. Self-shielding is not included in the simulation. Figure 4 shows the number of H i lines at a given distance from the main component that are detected in our Hydrodynamic simulation at $z = 2.9 - 3.0$ (similar figure to Figure 2). The distribution of H i lines are examined for three column density ranges, $13.5 < \log N_{HI} < 14.5$ cm$^{-2}$, $14.5 < \log N_{HI} < 15.5$ cm$^{-2}$, and $15.5 < \log N_{HI} < 16.5$ cm$^{-2}$. H i lines with relatively large column density, $\log N_{HI} > 14.5$, tend to cluster around the main components. On the other hand, weaker H i lines show the decrease in their number near the main components. These trends are similar to those seen in the observation results, although the components with $14.5 < \log N_{HI} < 15.5$ cm$^{-2}$ seem to be more concentrated in velocity in the simulated spectra.

In Figure 5, we show scatter plots between $\log N_{HI}$ and $b$ from the simulation. The difference of the distributions between HDLs and LDLs that we found in the observational result are successfully reproduced; strong HDLs with $\log N_{HI} > 15$ cm$^{-2}$ have Doppler parameters smaller than the extrapolation of $b_{min}$ for LDLs (eqn. (2)).

One of the differences between the observation and the simulation is that there is a blank region at $\log N_{HI} > 15$ cm$^{-2}$ and $b > 30$ km s$^{-1}$ only in the simulation. It may be because absorption lines at the region in the observation are not completely resolved even with our improved fitting method (especially in the case that only a few orders of Lyman series are available), and have large $b$-values compared to the values that we might see with very high S/N ratio. The minimum $b$-values, however, may be evaluated correctly even in such cases. On the other hand, the failure of the line deblending rarely happen in the simulation, because we have not included noise in the synthetic spectra, and because the resolution of our simulation, $256^3 \times 0.7h^1$ Mpc ($\Delta x = 2.7$ kpc), is high enough compared to the minimum resolution ($\Delta x = 37.5$ kpc) necessary to evaluate appropriate $b$-values (Bryan et al. 1999).

Another difference is that few narrow HDLs, whose Doppler parameter is smaller than the value given by eqn. (2), are detected at $\log N_{HI} < 15$ cm$^{-2}$ in the simulation (hereafter weak-narrow HDLs). Here, we would like to emphasize that the $b$-values of H i lines near the strong H i absorbers could be over-estimated in the simulation since we did not include self-shielding and shadowing effects that can be effective for the HDLs. We discuss this in the next section.
5. Summary and Discussion

In this paper, we, for the first time, separated H i absorption lines into HDLs and LDLs, and we find differences between them using 40 quasar spectra. For weak H i lines (i.e. LDLs), the correlation between column density and the minimum Doppler parameter have been often investigated in both of the observation and the simulation. It is thought that this relation arises by the mechanism that higher column density clouds appear to be associated with denser regions in which the gas is adiabatically compressed and heated (e.g. Kim, Cristiani, & D’Odorico 2001, 2002). Kim, Cristiani, & D’Odorico (2001, 2002) also suggested that for weak H i lines the slope of the log $N_{HI} - b_{min}$ relation became flatter as $z$ decreased at $z > 3$, though there was no such significant trend at lower redshift $z \sim 2$. We, however, do not find any redshift evolution in our sample (Figure 6 and 7).

The log $N_{HI} - b_{min}$ relation for HDLs is clearly shallower than the extrapolated relations for weak H i lines in KT97 and Zhang et al. (1997), while the relation for LDLs is good agreed with the past results. This means that HDL absorbers have relatively small Doppler parameters compared with the LDL absorbers at the same column density.

Davé et al. (1999) classify the H i gas clouds into three phases; (i) a cool low-density phase, (ii) a shock-heated intermediate-density phase, and (iii) a cold dense phase in galaxies. The first phase with relatively low column densities of log $N_{HI} \leq 15$ cm$^{-2}$ make the positive correlation between log $N_{HI}$ and $b_{min}$, while the last phase with large column densities makes an anti-correlation.

When we think about H i clouds in the cold dense phase, the effect of radiative cooling must be taken into consideration. Such dense clouds with log $N_{HI} \geq 17$ cm$^{-2}$ (i.e. LLSs and DLA systems) can shield themselves against the background UV flux, which preserves more H i (i.e. shielding effect). A similar effect may happen in the low column density clouds if they are located near the high column density clouds (i.e. shadowing effect). These effects are important at least at $z \geq 6$ (Nakamoto, Umemura, & Susa 2001), although they have not yet evaluated quantitatively at lower redshift because of high complexity after the formations of first stars and quasars. Zhang et al. (1995) also pointed out the importance of the shielding effect, though they did not include the effect in their simulation, and nor did we here. If plenty of H i gas is preserved, the cooling of H i gas becomes very effective in regions in photoionization equilibrium (H i line cooling is the most effective cooling factor at $T \sim 10^4$ K), which could lower the temperature, and decrease the value of the minimum Doppler parameter. Both of these effects will tend to produce weak-narrow HDLs in the log $N_{HI} - b$ plane, which makes the distribution of H i lines in the simulation more consistent with the observation for the HDLs.

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Fig. 1.— Observed and modeled velocity map for 10 Lyman series lines of the H i at $z_{\text{abs}} = 3.321$ in the spectrum of Q0014+8118. The lower line in each panel is the $1\sigma$ error. Tick marks denote the positions of H i absorption lines, and the large one at the center is the position of the main component.

Fig. 2.— Distribution of 973 H i lines, including the main components, in 100 km s$^{-1}$ wide bins from the main components.

Fig. 3.— Doppler parameter vs. column density. Open and filled circles are LDLs and HDLs, respectively. LDLs and HDLs with $b < 15$ km s$^{-1}$ are marked with small circles. Solid line is the relation between the column density $\log N_{\text{HI}}$ and the minimum Doppler parameter $b_{\text{min}}$ in KT97 ($12 < \log N_{\text{HI}} < 15$ cm$^{-2}$), and dotted line is the same relation extrapolated up to $\log N_{\text{HI}} = 18$ cm$^{-2}$. Dashed line is the same relation for HDLs in our sample. The pure thermal Doppler parameters corresponding to the temperatures, $T = 10^4, 5 \times 10^4, 10^5,$ and $2 \times 10^5$ K are shown with the thin dot-dashed horizontal lines.

Fig. 4.— Same as Figure 2, but the result from the Hydrodynamic simulation, except that the column density ranges of three subsamples are slightly different.

Fig. 5.— Similar to Figure 3, but from the Hydrodynamic simulation. Crosses are weak H i lines with $\log N_{\text{HI}} < 15$ cm$^{-2}$. Open square and triangle are completely deblended ($b < 40$ km s$^{-1}$) H i lines with the column densities of $15 < \log N_{\text{HI}} < 17$ cm$^{-2}$ and $\log N_{\text{HI}} > 17$ cm$^{-2}$, respectively. In contrast with Figure 3, We do not use the open squares for all lines within 200 km s$^{-1}$ of lines with $\log N_{\text{HI}} > 15$ cm$^{-2}$. Solid-and-dotted line and dashed line denote the relation between $\log N_{\text{HI}}$ and $b_{\text{min}}$ for LDLs (eqn. (2)) and HDLs (eqn. (3)) from the observational results.

Fig. 6.— Column density vs. Doppler parameter relation for HDLs at $z > 2.9$ and $z < 2.9$. We chose $z = 2.9$ when dividing H i sample into two subsamples because it makes the numbers of H i systems in them nearly identical.

Fig. 7.— Same as Figure 6, but the result for LDLs.
Table 1. Clustering properties of H I lines

| (1)  | (2)  | (3)  | (4)  | (5)  | (6)  |
|------|------|------|------|------|------|
|      |      |      |      |      |      |
| log $N_{HI}$ (cm$^{-2}$) | $\xi(50 - 100)^a$ | $\xi(100 - 150)^a$ | $\xi(150 - 200)^a$ | $v^b$ (km s$^{-1}$) | $n^c$ |
| 12 — 19 | 0.17$^{+0.06}_{-0.06}$ | 0.08$^{+0.05}_{-0.05}$ | 0.11$^{+0.06}_{-0.06}$ | 200 | 972 |
| 12 — 13 | 0.52$^{+0.28}_{-0.24}$ | 0.16$^{+0.25}_{-0.21}$ | $-0.10_{-0.18}^{+0.22}$ | 100 | 244 |
| 12 — 14 | 0.33$^{+0.08}_{-0.08}$ | $-0.00_{-0.07}^{+0.07}$ | 0.04$^{+0.07}_{-0.07}$ | 100 | 716 |
| 12 — 15 | 0.21$^{+0.06}_{-0.06}$ | 0.01$^{+0.06}_{-0.06}$ | 0.06$^{+0.06}_{-0.06}$ | 100 | 866 |
| 12 — 16 | 0.20$^{+0.06}_{-0.06}$ | 0.05$^{+0.06}_{-0.06}$ | 0.10$^{+0.06}_{-0.06}$ | 100 | 933 |
| 13 — 19 | 0.19$^{+0.08}_{-0.08}$ | 0.07$^{+0.07}_{-0.07}$ | 0.15$^{+0.08}_{-0.08}$ | 200 | 728 |
| 14 — 19 | 1.22$^{+0.30}_{-0.30}$ | 0.79$^{+0.31}_{-0.27}$ | 0.40$^{+0.28}_{-0.24}$ | 200 | 256 |
| 15 — 19 | 4.03$^{+1.49}_{-1.17}$ | 0.78$^{+1.06}_{-0.70}$ | 1.02$^{+1.09}_{-0.74}$ | 200 | 106 |
| 16 — 19 | 1.60$^{+5.90}_{-2.15}$ | 3.76$^{+6.28}_{-3.08}$ | 3.55$^{+6.00}_{-2.94}$ | 200$^d$ | 39 |

$^a$correlation and the 1σ Poisson error for the velocity separations of 50 – 100, 100 – 150, and 150 – 200 km s$^{-1}$.

$^b$velocity width at which the lower 1σ deviation of $\xi(v)$ first goes below $\xi(v)$=0 over $v > 50$ km s$^{-1}$.

$^c$number of H I lines.

$^d$we prefer to list $v = 200$ km s$^{-1}$, though the lower 1σ deviation of $\xi(v)$ goes below $\xi(v)$=0 at $50 \leq v < 100$ km s$^{-1}$; this could be due to the small sample.
Fig. 1: Velocity map of H I system at $z_{\text{abs}} = 3.321$ in the spectrum of Q0014+8118.
Fig. 2: Distribution of H\textsc{i} lines in 100 km s\textsuperscript{-1} bins from the main components.
Fig. 3: Column density — Doppler parameter relation for the observation.
Fig. 4: Same figure as Figure 2, but the result from the simulation.
Fig. 5: Same figure as Figure 3, but the result from the simulation.
Fig. 6: Column density — Doppler parameter relation for HDLs at $z > 2.9$ and $z < 2.9$. 
Fig. 7: Same figure as Figure 3, but the result for LDLs.