THE SDSS DAMPED Lyα SURVEY: DATA RELEASE 3
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ABSTRACT
We present the results from a damped Lyα survey of the Sloan Digital Sky Survey, Data Release 3. We have discovered over 500 new damped Lyα systems at z > 2.2, and the complete statistical sample for z > 1.6 has more than 600 damped Lyα galaxies. We measure the H I column density distribution f_{HI}(N, X) and its zeroth and first moments (the incidence of Lyα absorption systems and gas mass density Ω^{DLA}_g) as a function of redshift. The key results include: (1) the full SDSS DR3 f_{HI}(N, X) distribution (z ∼ 3.06) is well fit by a Π function (or double power law) with “break” column density N_g = 10^{21.5 ± 0.1} cm^{-2} and “faint-end” slope α = −1.8 ± 0.1; (2) the shape of the f_{HI}(N, X) distributions in a series of redshift bins does not show evolution; (3) the incidence and gas mass density of damped systems decrease by 35% ± 9% and 50% ± 10% during 1 Gyr between the redshift intervals z = [3.0, 3.5] and z = [2.2, 2.5]; and (4) the incidence and gas mass density of damped Lyα systems in the lowest SDSS redshift bin (z = 2.2) are consistent with the current values. We investigate a number of systematic errors in damped Lyα analysis and identify only one important effect: we measure 40% ± 20% higher Ω^{DLA}_g values toward a subset of brighter quasars than toward a faint subset. This effect is contrary to the bias associated with dust obscuration and suggests that gravitational lensing may be important. Comparing the results against several models of galaxy formation in ΛCDM, we find that all of the models significantly underpredict Ω^{DLA}_g at z = 3, and only SPH models with significant feedback can reproduce Ω^{DLA}_g at high redshift. Based on our results for the damped Lyα systems, we argue that the Lyman limit systems contribute 33% of the universe’s H I atoms at all redshifts z < 2.5. Furthermore, we infer that the f_{HI}(N, X) distribution for N_{HI} < 10^{20} cm^{-2} has an inflection with slope d log f/d log N > −9. We advocate a new mass density definition, the mass density of predominantly neutral gas Ω^\text{neutral}_g, to be contrasted with the mass density of gas associated with H I atoms. We contend the damped Lyα systems contribute >80% of Ω^\text{neutral}_g at all redshifts and therefore are the main reservoirs for star formation.

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

Online material: color figures, machine-readable tables

1. INTRODUCTION
The damped Lyα systems are the class of quasar absorption line systems with H I column density N_{HI} ≥ 2 × 10^{20} cm^{-2} (see Wolfe et al. 2005, for a review). Unlike the Lyα forest, the damped Lyα systems are composed of predominantly neutral gas and are proposed to be the progenitors of galaxies like the Milky Way (e.g., Kauffmann 1996). Wolfe (1986) established the N_{HI} = 2 × 10^{20} cm^{-2} threshold primarily to correspond to the surface density limit of local 21 cm observations at that time. It is somewhat fortuitous that this threshold roughly corresponds to the transition from primarily ionized gas to predominantly neutral gas (e.g., Viegas 1995; Prochaska & Wolfe 1996; Prochaska 1999; Vladilo et al. 2001).

For the past two decades, several groups have surveyed high z quasars for the damped Lyα systems (Wolfe et al. 1986; Wolfe et al. 1995; Storrie-Lombardi et al. 1996; Storrie-Lombardi & Wolfe 2000; Péroux et al. 2003). These surveys measured the H I frequency distribution function and its moments, the incidence of the damped Lyα systems Ω^{DLA}_g and the gas mass density of these galaxies Ω^{DLA}_g. The latter quantity has cosmological significance. Its evolution constrains the build-up of structure within hierarchical cosmology (e.g., Ma & Bertschinger 1994; Klypin et al. 1995), it serves as an important neutral gas reservoir for star formation at high redshift and describes the competition between gas accretion and star formation (e.g., Fall & Pei 1993), and it constrains models of galaxy formation in hierarchical cosmology (e.g., Somerville et al. 2001; Cen et al. 2003; Nagamine et al. 2004). Previous surveys have reported statistical error on Ω^{DLA}_g of ≈30% in redshift intervals ∆z ≈ 0.5 at high redshift. As we enter the so-called era of precision cosmology, we aspire to constrain Ω^{DLA}_g to better than 10%. Although not formally a cosmological parameter, a precise determination of Ω^{DLA}_g and its redshift evolution are fundamental constraints on any cosmological theory of galaxy formation.

In Prochaska & Herbert-Fort (2004, hereafter PH04), we initiated a survey for the damped Lyα systems in the quasar spectra of the Sloan Digital Sky Survey (SDSS) Data Release 1 (DR1). We demonstrated that the spectral resolution, signal-to-noise ratio (S/N), and wavelength coverage of the SDSS spectra are well suited to survey the damped Lyα systems at z > 2.2. We reported on the number of damped Lyα systems per unit redshift and the neutral gas mass density. In this paper, we extend the survey to include the full Data Release 3 (DR3; Abazajian et al. 2003). In addition to substantially increasing the PH04 sample, this paper extends the analysis to include a determination of the N(H I) frequency distribution, f_{HI}(N, X). Furthermore, we perform a series of tests to examine systematic errors related to the
analysis. With the increased sample size, we believe that the systematic uncertainty is as important as statistical uncertainty. Similarly, uncertainty related to selection bias (e.g., dust obscuration) must be given careful attention. Future progress will require significant advancements on each of these three fronts.

This paper is organized as follows: §2 describes the SDSS quasar sample and defines the subset used to survey the damped Lyα systems; we present the damped Lyα candidates and the N_H measurements in §3, perform standard analysis of the H i distribution in §4, and discuss the results in §6. Except for comparisons to local observations, we mainly restrict the analysis to optical surveys for the damped Lyα systems (i.e., z > 1.6).

Unless otherwise stated, all log values and expressions correspond to log base 10. Here and throughout the paper we adopt cosmological parameters consistent with the latest Wilkinson Microwave Anisotropy Probe (WMAP) results (Bennett et al. 2003): Ω_m = 0.7, Ω_r = 0.3, and H_0 = 70 km s^{-1} Mpc^{-1}.

2. SDSS SAMPLE

2.1. Redshift Path

The quasar sample considered in this paper includes every object identified spectroscopically as a quasar with z > 2.2 in the SDSS DR3. We also include the full compilation of quasars and damped Lyα systems (avoiding duplication) from the previous two decades of research, as compiled by Péroux et al. (2003). In each of these SDSS quasars we have defined a redshift interval over which we search for the presence of damped Lyα systems. In this paper, we define the redshift path using an algorithm similar to that introduced in PH04. We also apply more conservative criteria to investigate the effects of S/N (the estimated flux divided by estimated noise).

The starting redshift z_i is defined as follows. First, we identify the minimum wavelength λ_i where the median S/N in a 20 pixel interval exceeds S/N_{lim}. In PH04, we took S/N_{lim} = 4, and in this paper we also consider larger values. An assumption of our prescription is that the median S/N does not decrease significantly at wavelengths greater than λ_i, unless a damped Lyα candidate is present. This is a good assumption unless λ_i coincides with the Ly/β/O vi emission feature of the quasar. At these wavelengths the S/N of the data is elevated, and it is possible the median S/N may be above S/N_{lim} in this spectral region but below S/N_{lim} otherwise. Therefore, in the 10,000 km s^{-1} region centered at λ = 1025.7 (1 + z_{QSO}) we demand that the median S/N be greater than 3 × S/N_{lim} if λ_i is to be set within that region. In practice, this removes from the sample a number of faint quasars whose spectra have median S/N greater than S/N_{lim} only in the Ly/β/O vi emission line. Finally, we define the starting redshift for the damped Lyα search,

\[ z_i \equiv (\lambda_i/1215.67) - 1.005, \]

where the 0.005 increment offsets z_i by 1500 km s^{-1}. Finally, we require z_i ≥ 2.2. Similarly, we define an ending redshift for the statistical path length of a given quasar,

\[ z_f \equiv 0.99z_{QSO} - 0.01, \]

which corresponds to 3000 km s^{-1} blueward of the Lyα emission feature. The offset minimizes the likelihood that a damped Lyα system is physically associated with the quasar. For reasons unknown to us, a small fraction of the quasar spectra have extended regions (>50 pixels) with zero flux and null values in their error array. In these cases, we set z_f to 1000 km s^{-1} blueward of the “null region.”

Each quasar spectrum was visually inspected and characterized according to the presence or absence of features identified with intrinsic absorption (e.g., broad absorption line [BAL] quasars). This is a necessary step in damped Lyα surveys because quasars with strong intrinsic N v and O vi absorption can be confused with the Lyα transition of an intervening quasar absorption line system. Following PH04, we divided the quasars into three categories: (1) quasars without significant intrinsic absorption; (2) mild absorption-line quasars that show modest absorption at the C iv emission feature; and (3) strong absorption-line quasars whose C iv and O vi lines have large equivalent widths and could be confused with a damped Lyα system. The latter category is discarded from all subsequent analysis. For the mild absorption-line quasars, however, we search for damped Lyα systems in the redshift interval max (z_i, z_{BAL} < z < min(z_{QSO} - 0.08226, z_f)) where z_{BAL} \equiv (1 + z_{QSO}(1060/\lambda_{Lyα}) - 1), and the modification to the ending redshift minimizing the likelihood of misidentifying N v absorption as a damped Lyα system.

Table 1 presents the full list of SDSS DR3 quasars analyzed here. Columns (1)–(9) designate the SDSS plate, MJD, and fiber numbers, the quasar name, the emission redshift, a flag describing intrinsic absorption, z_i and z_f for S/N_{lim} = 4, and the absorption parameters consistent with the latest Wilkinson Microwave Anisotropy Probe (WMAP) results (Bennett et al. 2003): Ω_m = 0.7, Ω_r = 0.3, and H_0 = 70 km s^{-1} Mpc^{-1}.

| Plate | MJD | Fiber ID | Name | z_{QSO} | f_{BAL}^a | z_i | z_f | z_{candidate} |
|-------|-----|----------|------|---------|-----------|-----|-----|--------------|
| 650... | 52143 | 178 | J000050.60--102155.8 | 2.640 | 0 | 2.200 | 2.200 | 2.604 |
| 750... | 52235 | 550 | J000143.41+152021.4 | 2.638 | 0 | 2.200 | 2.200 | 2.602 |
| 650... | 52143 | 519 | J000159.12--094712.4 | 2.308 | 0 | 2.203 | 2.250 | 2.275 |
| 387... | 51791 | 556 | J000221.11+002149.4 | 3.057 | 0 | 2.200 | 2.209 | 3.016 |
| 650... | 52143 | 111 | J000238.41--101149.8 | 3.941 | 0 | 3.203 | ... | 3.891 |
| 750... | 52235 | 111 | J000300.34+160027.7 | 3.675 | 0 | 3.285 | 3.480 | 3.629 |

Note.—Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

a 0 = no intrinsic absorption; 1 = mild intrinsic absorption, included in analysis with restriction; 2 = strong intrinsic absorption, excluded.
b Starting redshift for S/N_{lim} = 5.
redshift of any damped Lyα candidates along the sight line. The latter may include candidates for which $z_{abs}$ is not in the $[z_1, z_f]$ interval. Many candidates are also false-positive detections, in particular of BAL absorption lines.

2.2. $g(z)$

The survey size of a quasar absorption-line study is characterized through the redshift sensitivity function $g(z)$. Figure 1 presents a series of $g(z)$ curves for the Large Bright Quasar Survey (LBQS) search for damped Lyα systems (Wolfe et al. 1995), the compilation of Péroux et al. (2003), and the SDSS DR1 sub-sample of PH04. These are compared against the full SDSS DR3 sample with $S/N_{lim} = 4$. Note that the SDSS data releases are inclusive and also that the Péroux et al. (2003) compilation includes the LBQS sample. Comparing the curves, we find that the current SDSS sample now exceeds the previous surveys by an order of magnitude at $z \sim 3$, by several times at $z \sim 4$, and by more than a factor of 10 at $z > 4.6$ (the gray dashed line in Fig. 1 traces the ratio of SDSS DR3 to the previous surveys). The dip at $z \sim 4$ in the ratio of SDSS DR3 to the previous surveys is largely due to the impressive high-z survey carried out by the Cambridge group. We also stress that the increased sensitivity of the SDSS DR3 at $z > 4$ should be viewed conservatively; follow-up observations should be performed to confirm the high-redshift results. In Figure 2 we show the $g(z)$ curves for several cuts on $S/N_{lim}$ and a sample selection for the SDSS DR3 quasars. These cuts are summarized in Table 2 and are referred to throughout the text.

In contrast to the $g(z)$ curves for the Lyα forest or Mg II systems (e.g., Prochter et al. 2005), there is no significant features due to strong sky lines. This is because in our algorithm the sky lines can only lead to false-positive detections, which are easily identified and ignored.

3. $N_{HI}$ Measurements

3.1. Damped Lyα Candidates

Damped Lyα candidates were identified in the quasar spectra using the same prescription introduced by PH04. In short, the algorithm compares the $S/N$ of the pixels in a running window of width $6(1+z)$ Å against $x_{S/N}$ specifically defined to be the median $S/N$ of the 151 pixels starting 200 pixels redward of the Lyα emission peak divided by 2.5, i.e., $x_{S/N} \equiv S/N$ of the quasar continuum just redward of Lyα emission. Furthermore, $x_{S/N}$ is constrained to have a minimum value of 1 and a maximum value of 2. If the fraction of pixels with $S/N \geq x_{S/N}$ is $\leq 60\%$, a damped Lyα candidate is recorded at the center of the window. This candidate list is supplemented by systems associated with relatively strong metal-line transitions outside the Lyα forest (S. Herbert-Fort et al. 2005, in preparation). Finally, the list is further supplemented by our visual inspection of each quasar spectrum when characterizing its intrinsic absorption. The damped Lyα candidates are listed in Table 1.

In PH04, we reported that Monte Carlo tests of our automated algorithm on synthetic spectra implied an idealized damped Lyα completeness of $\sim 95\%$ for $N_{HI} \approx 2 \times 10^{20}$ cm$^{-2}$ and 100% for $\log N_{HI} > 20.4$. Given the supplemental candidates from the metal-line search and our visual inspection, we believe the completeness definitely exceeds 95% for all absorbers with $N_{HI} > 2 \times 10^{20}$ cm$^{-2}$. We discuss a new set of completeness tests below.

Every damped Lyα candidate was subjected to the following analysis. First, the Lyα profile was visually inspected and obvious false-positive candidates were eliminated. This visual analysis included overplotting a Lyα profile with $N_{HI} = 2 \times 10^{20}$ cm$^{-2}$. To minimize the labor of fitting Lyα profiles, we chose not to fit many systems in which the overplotted profile was clearly a poor solution. It was our experience that nearly all of these candidates have best-fit values $N_{HI} < 1.5 \times 10^{20}$ cm$^{-2}$. Second, we searched

| Table 2 | SDSS Cuts |
|---------|-----------|
| Label   | $S/N_{lim}$ | CLR | $n_{DLA}$ |
| SDSS DR3_4............. | 4      | no  | 525  |
| SDSS DR3_4C............ | 4      | yes | 340  |
| SDSS DR3_5.........    | 5      | no  | 395  |
| SDSS DR3_5C........... | 5      | yes | 183  |
| SDSS DR3_8....         | 8      | no  | 155  |
| SDSS DR3_8C........... | 8      | yes | 88   |

* This entry refers to whether the quasar sample adheres to the color criteria described by Richards et al. (2002). In practice, we perform the color cut by only including quasars drawn from plates 761 and higher.
for metal-line absorption at redshifts near the estimated redshift centroid of the Ly$\alpha$ profile. The extensive wavelength coverage of SDSS spectra is a tremendous advantage in the analysis of damped Ly$\alpha$/C$\text{II}$ candidates. In general, we focused on the strongest low-ion transitions observed in the damped Ly$\alpha$/C$\text{II}$ systems (e.g., Prochaska et al. 2003b): Si$\text{II}$ $\lambda$1260, 1304, 1526, O$\text{I}$ $\lambda$1302, C$\text{II}$ $\lambda$1334, Al$\text{II}$ $\lambda$1670, and Fe$\text{II}$ $\lambda$1608, 2382, 2600. We characterized the metal-line absorption for each candidate as: (1) no metals detected, (2) weak or ambiguous metal absorption, and (3) secure metal-line absorption. Damped Ly$\alpha$/C$\text{II}$ candidates in the latter category generally exhibit two or more metal-line features outside the Ly$\alpha$ forest. For damped Ly$\alpha$/C$\text{II}$ systems with secure metal-line absorption, we constrain the subsequent Ly$\alpha$/C$\text{II}$ profiles to coincide with the metal-line redshift.

3.2. Ly$\alpha$ Fits

Those damped Ly$\alpha$ candidates that were not rejected by visual inspection were fitted with Voigt profiles in a semiquantitative fashion. As discussed by Prochaska et al. (2003b), systematic error associated with continuum placement and line blending generally dominates the statistical error associated with Poisson noise in the quasar flux. We have fitted the Ly$\alpha$ profile with an IDL tool x_fitdla, which allows the user to interactively modify the Voigt profiles and continuum placements. We then estimated a conservative uncertainty to each $N_{\text{HI}}$ value based on the constraints of the quasar continuum near the Ly$\alpha$ profile, the degree of line blending, and the Poisson noise of the data. Bolton et al. (2004) have emphasized that the SDSS spectroscopic data have non-Gaussian fluctuations, e.g., 3 $\sigma$ departures from the “true” value with higher than 0.27% frequency. Therefore, we have generally ignored single pixel outliers when performing the Ly$\alpha$ fits.

To be conservative, we adopt a minimum uncertainty of 0.15 dex in log $N_{\text{HI}}$ for the absorption systems with unambiguous metal-line detections, and 0.20 dex otherwise. These uncertainties are larger than those reported in PH04. As noted above, the effects of line blending and continuum uncertainty dominate the measurement uncertainty of the $N_{\text{HI}}$ values. Furthermore, it is very unlikely that the errors related to these systematic effects are Gaussian distributed. At present, it is very difficult to accurately

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Fig. 3.—Example profile fits to four damped Ly$\alpha$ systems from our SDSS DR3 survey. The examples represent (a) a high-S/N case with a well-constrained quasar continuum and minimal line blending [$\sigma(N_{\text{HI}}) = 0.15$]; (b) a low-S/N case [$\sigma(N_{\text{HI}}) = 0.30$]; (c) an example with severe line blending [$\sigma(N_{\text{HI}}) = 0.20$]; and (d) an example in which determining the redshift from associated metal-line absorption is very important [$\sigma(N_{\text{HI}}) = 0.15$]. [See the electronic edition of the Journal for a color version of this figure.]
assess the magnitude and distribution of the errors in the \( N_{\text{HI}} \) values. Below we discuss an attempt based on the analysis of mock spectra, yet even this approach has limited value. Nevertheless, we contend that 95\% of the true \( N_{\text{HI}} \) values will lie within 2 \( \sigma \) of the reported \( N_{\text{HI}} \) values, but we cannot argue that the reported errors are Gaussian distributed. This remains a significant failing in the analysis of DLA surveys.

Figure 3 shows four example profile fits from the SDSS sample, which illustrate several of the key issues. In Figure 3a we present a high-S/N case with a well-constrained quasar continuum and the redshift centroided by metal-line detections. The fit is constrained by data in both the core and wings of the \( \text{Ly}\alpha \) profile, and the adopted 0.15 dex uncertainty is overly conservative. Figure 3b presents a low-S/N case. In this case, it is very difficult to constrain the fit based on the core of the \( \text{Ly}\alpha \) profile. Nevertheless, the continuum level is reasonably well constrained, and the wings of the profile set the \( N_{\text{HI}} \) value. Figure 3c presents a case in which line-blending is severe and the \( N_{\text{HI}} \) value is only constrained by the wings of the profile. In these cases the continuum placement is critical. Finally, Figure 3d emphasizes the importance of metal-line detection. In this example, the \( \text{Ly}\alpha \) profile is centered on the redshift of the metal-line transitions. Without this constraint, we would have centered the \( \text{Ly}\alpha \) profile a few angstroms redward of the current position and derived a larger \( N_{\text{HI}} \) value. We suspect that some damped \( \text{Ly}\alpha \) systems without metal-line detections have \( N_{\text{HI}} \) values that are biased high (\( \approx 0.1-0.2 \) dex). Of course, these damped \( \text{Ly}\alpha \) systems tend to have lower \( N_{\text{HI}} \) values, and this systematic effect is primarily an issue only for candidates with \( N_{\text{HI}} \approx 2 \times 10^{20} \text{ cm}^{-2} \). Finally, we should stress that the \( N_{\text{HI}} \) values of damped \( \text{Ly}\alpha \) candidates near the quasar \( \text{O VI} \) or \( \text{Ly}\alpha \) emission features are difficult to constrain because of uncertain continuum placement.

All of the fits from the DR3 sample and the \( \text{Ly}\alpha \) fits from are available on our Web site. In addition to postscript plots, we provide the files (IDL format) that contain the \( \text{Ly}\alpha \) fits and quasar continua, and also a description of the software used to perform the fits. Interested readers can reanalyze any of our \( \text{Ly}\alpha \) fits.

Tables 3–5 present the \( N_{\text{HI}} \) values for the damped \( \text{Ly}\alpha \) systems comprising the statistical sample, the damped \( \text{Ly}\alpha \) systems discovered that are not in any of our statistical samples, and all of the damped \( \text{Ly}\alpha \) candidates with central \( N_{\text{HI}} \) values less than \( 2 \times 10^{20} \text{ cm}^{-2} \) (termed super-LLS). In Table 3 we list the damped \( \text{Ly}\alpha \) absorption redshift, indicate its membership within the various statistical cuts, list the data release of the actual spectrum analyzed, present the metal-line characteristics, and list the \( N_{\text{HI}} \) value and error. The nonstatistical damped \( \text{Ly}\alpha \) sample presented in Table 4 comprises damped \( \text{Ly}\alpha \) systems with \( z_{\text{abs}} \approx z_{\text{QSO}}, z_{\text{abs}} < z_{\text{i}}, \) and/or systems toward quasars with strong intrinsic absorption. We present this table for completeness. We emphasize that while the absorbers listed in Table 5 have a central value below \( 2 \times 10^{20} \text{ cm}^{-2} \), the true \( N_{\text{HI}} \) value of many of these absorbers will exceed the damped \( \text{Ly}\alpha \) threshold.

3.3 Completeness Tests and \( N_{\text{HI}} \), Accuracy

There are several tests one can perform to assess the reliability and completeness of the \( N_{\text{HI}} \) analysis. A valuable test of the \( N_{\text{HI}} \) accuracy is to compare the SDSS measurements to values derived from observations at higher spectral resolution and/or S/N. Over the past several years, we have observed a subset of the SDSS damped \( \text{Ly}\alpha \) sample for other scientific studies (e.g., chemical evolution and C ii analysis; Prochaska et al. 2003a; Wolfe et al. 2004) with the Echellette Spectrometer and Imager (ESI; Sheinis et al. 2002). Figure 4 compares the values of the SDSS fits with those derived from the ESI spectra. The agreement is excellent. It is important to note, however, that the fits

Table 4

SDSS DR3 DLA NONSTATISTICAL SAMPLE

| Name               | \( z_{\text{abs}} \) | DR | \( f_{\text{abs}} \) | \( \log N_{\text{HI}} \) |
|--------------------|----------------------|----|---------------------|---------------------|
| J001115.2+144601.8  | 3.4523               | 2  | 2                   | 21.65 ± 0.20        |
| J001134.5+151517.4  | 4.3175               | 2  | 1                   | 20.50 ± 0.20        |
| J001134.5+151517.4  | 4.3592               | 2  | 2                   | 21.10 ± 0.20        |
| J004995.9-093035.6  | 3.2858               | 2  | 2                   | 20.70 ± 0.20        |
| J014214.7+002324.3  | 3.3482               | 1  | 2                   | 20.40 ± 0.15        |
| J020651.4-094141.3  | 2.4702               | 2  | 2                   | 20.30 ± 0.20        |
| J021232.1-100422.1  | 2.7140               | 1  | 0                   | 21.00 ± 0.15        |
| J023148.8-073906.3  | 2.2982               | 3  | 2                   | 21.75 ± 0.20        |
| J033344.4-060625.1  | 3.9349               | 3  | 2                   | 21.60 ± 0.20        |
| J073149.5+285448.7  | 2.6859               | 2  | 1                   | 20.55 ± 0.15        |

Note.—Table 4 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

\( f_{\text{abs}} \) = no metals; 1 = weak metals; 2 = metals detected.

Table 5

SDSS DR3 SUPER-LLS SAMPLE

| Name               | \( z_{\text{abs}} \) | DR | \( f_{\text{abs}} \) | \( \log N_{\text{HI}} \) |
|--------------------|----------------------|----|---------------------|---------------------|
| J001328.2+135828.0  | 2.6123               | 3  | 5                   | 20.10 ± 0.15        |
| J002614.6+141310.5  | 3.9032               | 2  | 5                   | 20.20 ± 0.15        |
| J004732.7+002111.3  | 2.4687               | 2  | 5                   | 20.25 ± 0.15        |
| J013317.7+144300.3  | 2.9766               | 2  | 8                   | 20.15 ± 0.15        |
| J014609.3-092918.2  | 3.6084               | 2  | 8                   | 20.25 ± 0.15        |
| J021143.3-084723.8  | 2.2684               | 2  | 4                   | 20.10 ± 0.15        |
| J021123.1-100422.1  | 2.2738               | 1  | 8                   | 20.25 ± 0.15        |
| J025039.1-065405.1  | 4.3894               | 3  | 4                   | 20.00 ± 0.15        |
| J031036.8+005521.7  | 3.1142               | 2  | 5                   | 20.20 ± 0.15        |

Note.—Table 5 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

\( f_{\text{abs}} \) = no metals; 1 = weak metals; 2 = metals detected.

Available at: http://www.ucolick.org/~xavier/SDSSDLA/index.html.
were performed primarily by one of us (J. X. P.) and that the systematic error related to continuum placement is likely correlated. Similarly, the effects of line blending are qualitatively similar for the two data sets. Indeed, the reduced $\chi^2 = 0.4$ indicates that the estimated uncertainties significantly exceed the statistical uncertainty. There is a notable case in PH04 (at $z = 2.77$ toward J084407.29+515311) for which the SDSS value is 0.3 dex higher than the ESI value due to improper continuum placement in the SDSS analysis. We believe that this one case was the result of our initial inexperience with the SDSS spectra and that such errors are very rare in the current analysis. Nevertheless, it does underscore the fact that the error in the $N_{\text{HI}}$ values are predominantly systematic and in some cases large.

One qualitative assessment of sample completeness is an inspection of the $N_{\text{HI}}$ distribution. Figure 5 presents a histogram of $N_{\text{HI}}$ values for all of the fitted damped Ly$\alpha$ candidates. The distribution shows a steady increase to lower $N_{\text{HI}}$, value that extends just below $2 \times 10^{20}$ cm$^{-2}$. We note that the relatively steep decline in the distribution at $N_{\text{HI}} < 10^{20.2}$ cm$^{-2}$ is partly due to incompleteness in our search algorithm. It is also due to the fact that we eliminated many damped Ly$\alpha$ candidates after visual inspection.

Since the publication of PH04, we have performed a damped Ly$\alpha$ survey on a new set of mock spectra kindly provided by P. McDonald. These mock spectra were carefully constructed to match the S/N and redshifts of the full SDSS DR3 quasar sample. A synthetic Ly$\alpha$ forest was added to the quasar continuum according to the prescriptions detailed in McDonald et al. (2005b). Finally, a random set of damped Ly$\alpha$ systems (with a column density frequency distribution similar to the results below) were added to the spectra, along with a set of Lyman limit systems with $N_{\text{HI}} = 1 \times 10^{17}$ to $2 \times 10^{20}$ cm$^{-2}$, following the prescriptions of McDonald et al. (2005a). We analyzed these mock spectra using the same algorithms as the scientific search and recovered 99% of the damped Ly$\alpha$ systems. The few that we did not “discover” have $N_{\text{HI}} < 10^{20.4}$ cm$^{-2}$ and just missed satisfying the damped Ly$\alpha$ candidate criteria. Furthermore, we recovered 90% of the absorbers with $N_{\text{HI}} \approx 1 \times 10^{20}$ cm$^{-2}$. Therefore, we are confident that the sample is nearly complete, although it is likely we are missing $\approx 5\%$ of the absorbers with $N_{\text{HI}} \approx 2 \times 10^{20}$ cm$^{-2}$.

To further investigate uncertainty in our $N_{\text{HI}}$ measurements, we fitted Voigt profiles to 50 of the damped Ly$\alpha$ systems from the mock spectra. With only one exception, our fitted values are within 0.3 dex of the true value. In this one exception we fitted one damped Ly$\alpha$ profile to a case that was actually two damped systems separated by $\approx 500$ km s$^{-1}$. In practice, this situation can be accounted for if both damped Ly$\alpha$ systems exhibit metal-line absorption. In any case, we expect these systems to be rare (Lopez & Ellison 2003); but they do introduce a nonzero systematic error to the damped Ly$\alpha$ analysis. In future papers, we will expand this type of mock analysis to probe other aspects of fitting errors and completeness limits for the SDSS samples.

4. RESULTS

In this section, we report the main results of the damped Ly$\alpha$ survey. These include the H$\text{I}$ frequency distribution function and its zeroth and first moments. It is amusing to note that many of the techniques are directly analogous to the derivation and analysis of galaxy luminosity functions. Indeed, we rely on many of the standard techniques and face similar challenges and systematic uncertainties.

4.1. $f_{\text{HI}}(N, X)$: The H$\text{I}$ Column Density Frequency Distribution

Following previous work (e.g., Lanzetta et al. 1991), we define the number of damped Ly$\alpha$ systems in the intervals $(N, N + dN)$ and $(X, X + dX)$:

$$f_{\text{HI}}(N, X) dN dX,$$

where $f_{\text{HI}}(N, X)$ is the frequency distribution, and the “absorption distance”

$$dX \equiv \frac{H_0}{H(z)} (1 + z)^2 dz.$$

With this definition, a nonevolving population of objects will have constant $f_{\text{HI}}(N, X)$ in time, provided one adopts the correct cosmology.
In Figure 6, we present $f_{\text{HI}}(N, X)$ for the full SDSS DR3.4 survey. This sample spans the redshift interval $z = [2.2, 5.5]$ with an integrated absorption path length $\Delta X = 7417.5$ and a $N_{\text{HI}}$-weighted mean redshift of 3.2. The solid points with error bars describe $f_{\text{HI}}(N, X)$ for $N_{\text{HI}}$ bins of $\Delta N = 0.1$ dex:

$$f_{\text{HI}}(N, X) = \frac{m_{\text{DLA}}(N, N + \Delta N)}{\Delta X},$$  \hspace{1cm} (5)

where $m_{\text{DLA}}$ is the number of damped Lyα systems within $(N, N + \Delta N)$ in the $\Delta X$ interval. The error bars reflect Poisson uncertainty (68.3% confidence level [c.l.]) according to the value of $m_{\text{DLA}}$, and the upper limits correspond to 95% c.l. The derivation of $f_{\text{HI}}(N, X)$ in this discrete manner is analogous to the derivation of galaxy luminosity functions using the $V_{\text{max}}$ method.

Lacking a physical model, we have considered three functional forms to describe $f_{\text{HI}}(N, X)$: (i) a single power law,

$$f_{\text{HI}}(N, X) = k_1 N^{\alpha_1},$$  \hspace{1cm} (6)

(ii) a $\Gamma$ function (e.g., Fall & Pei 1993),

$$f_{\text{HI}}(N, X) = k_2 \left( \frac{N}{N_H} \right)^{\alpha_2} \exp \left( -\frac{N}{N_H} \right),$$  \hspace{1cm} (7)

and (iii) a double power law,

$$f_{\text{HI}}(N, X) = k_3 \left( \frac{N}{N_d} \right)^{\beta},$$  \hspace{1cm} (8)

where $\beta = \begin{cases} \alpha_3 & N < N_d, \\ \alpha_4 & N \geq N_d. \end{cases}$

In each case, we perform a maximum likelihood analysis to constrain the functional parameters and set the normalization constants $k_1$, $k_2$, and $k_3$ by imposing the integral constraint

$$\int_{N_{\text{HI}}}^\infty f(N, X) dN = \frac{m_{\text{DLA}}}{\Delta X}.$$

To estimate the parameter uncertainties and construct a correlation matrix, we performed a “jackknife” analysis (e.g., Lupton 1993; Blanton et al. 2003). Specifically, we derived the best-fit parameters for 21 subsamples, ignoring 223 random quasars in each case. The parameter uncertainty is then given by

$$\sigma^2 = \frac{N - 1}{N} \sum_i (x_i - \bar{x})^2,$$  \hspace{1cm} (10)

with $N = 21$. In some cases these values are close to the one-parameter confidence limits derived from the maximum likelihood function, although there are notable exceptions. We calculate the correlation matrix in standard fashion (see Blanton et al. 2003),

$$r_{ij} = \frac{\langle \Delta x_i \Delta x_j \rangle}{\langle \Delta x_i^2 \rangle^{1/2} \langle \Delta x_j^2 \rangle^{1/2}},$$  \hspace{1cm} (11)

where

$$\langle \Delta x_i \Delta x_j \rangle = \frac{N - 1}{N} \sum_i (x_i - \bar{x})(x_j - \bar{x}).$$  \hspace{1cm} (12)

As is typically the case for fits to galaxy luminosity functions, we find significant correlations between the parameters. It is important to keep this in mind when comparing the fits to various redshift intervals. Table 6 presents the best-fit values for the parameters for the full SDSS DR3 sample and also the fits to the damped Lyα systems in several redshift intervals. In this table, the error bars refer to one-parameter uncertainties, which correspond to the 68% c.l. of the maximum likelihood function when keeping the other parameters fixed at their best-fit values. The exceptions are the normalization values, for which we have only reported the Poissonian error based on the best fit. Table 7 provides the parameter uncertainties and the correlation matrix for the full SDSS DR3.4 sample. When the absolute value of the off-diagonal terms is much less than 1, there is little correlation between the parameters. Unfortunately, there are too few damped Lyα systems in the redshift bins to perform a meaningful jackknife analysis for these subsets. We suspect, however, that the parameters are correlated in a way similar to the results presented in Table 7.

The best-fit solutions are overlaid on the binned evaluation of $f_{\text{HI}}(N, X)$ in Figure 6. First, consider the single power-law solution (dotted line) with a best-fit slope of $\alpha_1 = -2.21 \pm 0.05$. This functional form is a poor description of the data. A one-sided Kolmogorov-Smirnov (KS) test indicates there is a less than 0.1% probability that the cumulative distributions of the observations and the power law are drawn from the same parent population. In short, the power law is too steep at low $N_{\text{HI}}$ and too shallow at large $N_{\text{HI}}$. Although previous surveys suggested that a single power law was a poor description (e.g., Wolfe et al. 1995), their sample size was too small to rule out this solution. Note that this result contrasts the damped Lyα systems with the Lyα forest (absorbers with $N_{\text{HI}} < 10^{15}$ cm$^{-2}$), where a single power law with exponent $\alpha_1 \approx -1.5$ is a good description of the observations (e.g., Kirkman & Tytler 1997).

Although a single power law is a poor description of the observations, the fit does highlight an important new result: the $f_{\text{HI}}(N, X)$ distribution is steeper than a $N_{\text{HI}}^{-2}$ power law at large
column densities. We further develop this point in § 4.3. The other two curves on Figure 6 show the Ω (dashed line) and double power-law fit (dashed-dotted line). Both of these functional forms are a fair fit to the observations; a one-sided KS test gives values >10\% for the full 1 σ range of the parameters. Furthermore, there is good agreement between the “break” column densities (N₁ and N₂), and the power-law indices at low column densities are consistent. Both solutions indicate that f₁₁₁(N₁X) drops very steeply (α ≈ -2) at N₁ ≈ 10^{21.15} cm\(^{-2}\) and that the distribution has a faint-end slope of α ≈ -2.

In the following subsections, we consider evolution in the zeroth and first moments of f₁₁₁(N₁X). Figure 7 qualitatively describes the redshift evolution of the full f₁₁₁(N₁X) distribution. The figure plots f₁₁₁(N₁X) as a function of redshift against the f₁₁₁(N₁X) distribution of the full SDSS DR3 sample in four N₁₁ intervals: (1) 20.3 ≤ log N₁₁ < 20.6; (2) 20.6 ≤ log N₁₁ < 21.0; (3) 21.0 ≤ log N₁₁ < 21.4; and (4) 21.4 ≤ log N₁₁ < 21.8. At low N₁₁, f₁₁₁(N₁X) increases monotonically with redshift. The peak-to-peak range is modest, however, only evolving by a factor of ≈2. Similar evolution can be identified in the high-N₁₁ bins, with the exception of the highest redshift interval.

Perhaps the most important result is that the shape of f₁₁₁(N₁X) is independent of redshift. We have compared the f₁₁₁(N₁X) distributions from each redshift bin using a two-sided KS test. This test compares the shape of the distributions but is insensitive to the normalization. Our analysis found KS probabilities greater than 10\% for every pair of redshift intervals. Contrary to previous claims, therefore, there is no evidence for a significant evolution in f₁₁₁(N₁X) for the DLAs with redshift (e.g., a steeping beyond z = 3). With the current sample, there may only be a significant evolution in the normalization of f₁₁₁(N₁X).

4.2. \( \ell_{DLA}(X) dX: The Incidence of Damped Lyα Systems \)

The zeroth moment of f₁₁₁(N₁X) gives the number of damped Lyα systems encountered per unit absorption path length dX, i.e., the line density of damped Lyα systems.

\[
\ell_{DLA}(X) dX = \int_{N_{h}}^{\infty} f_{DLA}(N, X) dN dX. 
\]

The line density is related to the comoving number density of damped Lyα systems, \( n_{DLA}(X) \), and the cross section, \( A(X) \), as

\[
\ell_{DLA}(X) = (c/H_0)n_{DLA}(X) A(X). 
\]

In this manner, \( \ell_{DLA} \) is related to the covering fraction of damped Lyα systems on the sky.

Figure 8 shows \( \ell_{DLA}(X) dX \) for the damped Lyα systems at \( z > 1.6 \) and for the local universe (Zwaan et al. 2005; Rosenberg & Schneider 2003; Ryan-Weber et al. 2003, 2005). The values for the damped Lyα systems were calculated in the discrete limit, e.g.,

\[
\ell_{DLA}(X = m_{DLA}) = m_{DLA}/A(X),
\]

and the error bars reflect Poisson uncertainty in \( m_{DLA} \) (68.3\% c.l.). The solid line traces the value of \( \ell_{DLA}(X) \) derived in a

### Table 6

| Form                  | Parameters | \( z \in [2.2, 5.5]^a \) | \( z \in [1.7, 2.2] \) | \( z \in [2.2, 2.5] \) | \( z \in [2.5, 3.0] \) | \( z \in [3.0, 3.5] \) | \( z \in [3.5, 5.5] \) |
|-----------------------|------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Single                | \( \log k_1 \) = 23.16 ± 0.02 | 21.81 ± 0.08 | 27.15 ± 0.04 | 22.12 ± 0.03 | 20.84 ± 0.03 | 20.33 ± 0.04 |
|                      | \( \alpha_1 \) = -2.19 ± 0.05 | -2.13 ± 0.13 | -2.39 ± 0.13 | -2.14 ± 0.08 | -2.08 ± 0.09 | -2.20 ± 0.10 |
|                      | \( \log N_1 \) = 21.48 ± 0.05 | 21.31 ± 0.15 | 21.31 ± 0.20 | 21.56 ± 0.16 | 21.36 ± 0.12 | 21.69 ± 0.14 |
| Gamma                 | \( \log k_2 \) = -23.52 ± 0.02 | -23.03 ± 0.04 | -23.40 ± 0.04 | -23.70 ± 0.03 | -23.03 ± 0.03 | -23.99 ± 0.04 |
|                      | \( \alpha_2 \) = -1.80 ± 0.06 | -1.56 ± 0.13 | -1.94 ± 0.16 | -1.78 ± 0.09 | -1.52 ± 0.09 | -1.93 ± 0.12 |
|                      | \( \log N_2 \) = 21.50 ± 0.04 | 21.65 ± 0.15 | 21.50 ± 0.17 | 21.45 ± 0.12 | 21.45 ± 0.09 | 21.50 ± 0.20 |
|                      | \( \alpha_3 \) = -2.00 ± 0.06 | -1.96 ± 0.27 | -2.25 ± 0.17 | -1.94 ± 0.10 | -1.81 ± 0.11 | -2.03 ± 0.13 |
|                      | \( \alpha_4 \) = -6.00 ± 0.06 | -10.00 ± 7.8 | -10.00 ± 7.3 | -4.26 ± 2.2 | -5.72 ± 3.4 | -4.78 ± 2.6 |

### Table 7

| Parameter | \( \sigma \) | \( \delta \log k_1 \) | \( \delta \alpha_1 \) | \( \delta \log k_2 \) | \( \delta \log N_1 \) | \( \delta \alpha_2 \) | \( \delta \log N_2 \) | \( \delta \alpha_3 \) | \( \delta \alpha_4 \) |
|-----------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \delta \log k_1 \)  | 1.0 | 1.00 | -1.00 | -0.48 | 0.28 | -0.80 | -0.33 | -0.01 | -0.93 | -0.06 |
| \( \delta \alpha_1 \)  | 0.05 | -1.00 | 1.00 | 0.48 | -0.29 | 0.80 | 0.32 | 0.02 | 0.93 | 0.05 |
| \( \delta \log k_2 \)  | 0.29 | -0.48 | 0.48 | 1.00 | -0.98 | 0.91 | 0.47 | -0.25 | 0.66 | -0.28 |
| \( \delta \log N_1 \)  | 0.10 | 0.28 | -0.29 | -0.98 | 1.00 | -0.80 | -0.45 | 0.29 | -0.50 | 0.29 |
| \( \delta \alpha_2 \)  | 0.11 | -0.80 | 0.80 | 0.91 | -0.80 | 1.00 | 0.48 | -0.17 | 0.89 | -0.15 |
| \( \delta \log k_1 \)  | 0.18 | -0.33 | 0.32 | 0.47 | -0.45 | 0.48 | 1.00 | -0.93 | 0.61 | 0.53 |
| \( \delta \log N_2 \)  | 0.08 | -0.01 | 0.02 | -0.25 | 0.29 | -0.17 | -0.93 | 1.00 | -0.29 | -0.64 |
| \( \delta \alpha_3 \)  | 0.07 | -0.93 | 0.93 | 0.66 | -0.50 | 0.89 | 0.61 | -0.29 | 1.00 | 0.09 |
| \( \delta \alpha_4 \)  | 2.13 | -0.06 | 0.05 | -0.28 | 0.29 | -0.15 | 0.53 | -0.64 | 0.99 | 1.00 |

Note:—Restricted to the SDSS DR3-4 sample.
series of 0.5 Gyr time intervals to reveal any differences in binning. It is evident from Figure 8 that the line density of damped Lyα systems increases from $z = 2$ to 4; the increase between the $z = [2.2, 2.5]$ interval and the $z = [3.5, 5]$ bin is a factor of $1.7 \pm 0.2$. The largest change in $\ell_{\text{DLA}}(X)$ occurs during a $\Delta z = 1$ interval from $z \approx 2.3$ to 3.3, corresponding to $\Delta t = 800$ Myr. We discuss possible explanations for this evolution in § 6. Another interesting result is that $\ell_{\text{DLA}}(z \approx 2.3)$ is less than $2 \sigma$ larger than $\ell_{\text{DLA}}(z = 0)$, i.e., the data suggest little evolution in the line density of damped systems over the past $\approx 10$ Gyr. Within the context of hierarchical cosmology, this is a surprising result. It implies that when smaller galaxies merge and accrete other systems, the product of the comoving density and the total gas cross section satisfying the damped Lyα criterion is conserved. Perhaps this is related to the fact that the damped Lyα threshold is near the surface density threshold for star formation.

4.3. $\Omega_g$: The Cosmological Neutral Gas Mass Density

4.3.1. Definition of $\Omega_g$

The first moment of the $f_{\text{HI}}(N, X)$ distribution gives a cosmologically meaningful quantity, the gas mass density of H i atoms,

$$\Omega_g^{\text{HI}}(X) \equiv \frac{\mu m_0 H_0}{c p_c} \int_{N_{\text{min}}}^{N_{\text{max}}} N_{\text{HI}}, f_{\text{HI}}(N, X) \, dN$$ (16)

where $\mu$ is the mean molecular mass of the gas (taken to be 1.3), $H_0$ is the Hubble constant, and $p_c$ is the critical mass density. Traditional treatments of $\Omega_g^{\text{HI}}$ and damped Lyα systems have integrated equation (16) from $N_{\text{min}} = 2 \times 10^{20}$ cm$^{-2}$ to $N_{\text{max}} = \infty$, yielding $\Omega_0^{\text{DLA}}$. As emphasized by Péroux et al. (2003), $\Omega_g^{\text{DLA}}$ may be significantly less than $\Omega_g^{\text{HI}}$ if absorbers below the damped Lyα threshold contribute to the H i mass density. In this case, $\Omega_g^{\text{HI}}$ would include a large contribution from gas that is predominantly ionized, because the H i atoms in the Lyman limit systems are a mere trace of the gas. It is difficult, however, to assign any physical significance to $\Omega_g^{\text{DLA}}$ aside from a mere census of the H i atoms in the universe. In contrast, $\Omega_g^{\text{DLA}}$ offers a good estimate of the mass density of gas that is predominantly neutral (see below).

Below we consider both quantities, with primary emphasis on $\Omega_g^{\text{DLA}}$, because we contend it best defines the gas reservoir available for star formation at high redshift. In practice, $\Omega_g^{\text{DLA}}$ is generally evaluated in the discrete limit

$$\Omega_g^{\text{DLA}} = \frac{\mu m_0 H_0}{c p_c} \sum N_{\text{HI}},$$ (17)

where the sum is taken over the $N_{\text{HI}},$ measurements of the damped Lyα systems in a given redshift interval with total path length $\Delta X$.

In the following discussions we also consider several definitions for $\Omega_g$ based on the values of $N_{\text{min}}$ and $N_{\text{max}}$. Table 8 summarizes the various definitions.

4.3.2. Convergence of $\Omega_g$

Consider first the upper limit, $N_{\text{max}}$. To verify that $\Omega_g$ converges, it is necessary to integrate $f_{\text{HI}}(N, X)$ until

$$\frac{d \log f_{\text{HI}}(N, X)}{d \log N_{\text{HI}}} \ll -2,$$ (18)

i.e., until one establishes that $f_{\text{HI}}(N, X)$ is significantly steeper than a $N_{\text{HI}}^{-2}$ power law. As noted in § 4.1 and Figure 6, the $\Gamma$ function and double power-law fits to the $f_{\text{HI}}(N, X)$ distribution indicate that $f_{\text{HI}}(N, X)$ steepens at $N_{\text{HI}} \approx 10^{21.5}$ cm$^{-2}$. Furthermore, even a single power-law fit to the data almost satisfies equation (18). This point is emphasized in Figure 9, which presents the exponent of the best-fitting single power law to the SDSS DR3 $f_{\text{HI}}(N, X)$ distribution function as a function of the lower $N_{\text{HI}}$, bound to the distribution function, e.g., the point at $\log N_{\text{HI}} = 21$ shows the exponent for the single power-law fit to $f_{\text{HI}}(N_{\text{HI}} > 10^{21}$ cm$^{-2}$). Not surprisingly, the curve starts at $N_{\text{HI}} = 2 \times 10^{20}$ cm$^{-2}$ with $\alpha_1 = -2.2$ and decreases with increasing $N_{\text{HI}}$. In addition, it is important that the value of $\alpha_1$ decreases below $-3$ in Figure 9, because a power law with $\alpha_1 = -2.2$ converges very slowly with $N_{\text{max}}$. 

![Figure 7](image1.png)

![Figure 8](image2.png)
The results presented here are the first definitive demonstration that the H/ forest to \( \Omega_{\text{HI}} \) is negligible compared to absorbers with \( N_{\text{HI}} > 10^{15} \) cm\(^{-2}\).

4.3.3. Impact of the Lyman Limit Systems

Of greater interest to this discussion is the contribution of the Lyman limit systems\(^6\) to \( \Omega_{\text{HI}} \). Indeed, Péroux et al. (2003) claimed that Lyman limit systems with \( N_{\text{HI}} > 10^{19} \) cm\(^{-2}\) contribute \( \approx 50\% \) of \( \Omega_{\text{HI}} \) at \( z > 3.5 \). In PH04, we argued that Péroux et al. (2003) overstated the contribution of these "super-LLS" to \( \Omega_{\text{HI}} \), and in particular underestimated the uncertainty of their contribution. Let us return to this issue with the increased sample of SDSS DR3.

The first point to stress is that \( d \log f_{\text{HI}}(N, X)/d \log N_{\text{HI}} \approx -2 \) at \( N_{\text{HI}} \approx 10^{20.3} \) cm\(^{-2}\). This is sufficiently steep that absorbers with \( N_{\text{HI}} \approx 10^{20} \) cm\(^{-2}\) must contribute at least a few percent of \( \Omega_{\text{HI}} \). Indeed, if we extrapolate our fits to \( f_{\text{HI}}(N, X) \) for the damped Ly\( \alpha \) systems from \( N_{\text{HI}} = 2 \times 10^{20} \) cm\(^{-2}\) to \( 10^{21} \) cm\(^{-2}\), we find that the Lyman limit systems would give a larger neutral gas mass density than the value from the damped Ly\( \alpha \) systems.

\(^6\) Lyman-limit systems are defined to be all absorbers with optical depth exceeding unity at 1 Ryd. In this discussion, we generally restrict the definition to absorbers with \( 17.2 \leq \log (N_{\text{HI}}/\text{cm}^2) < 20.3 \). The one exception is the line density, as defined in equation (19).
extrapolations, however, significantly overpredict the line density of Lyman limit systems. Because the first derivative of this single power law is not continuous at the damped Lyα system threshold or the transition to the Lyα forest, it should be considered a lower limit. The contribution of the Lyman limit systems on the grounds that they are highly uncertain in $\Omega_{g}^{LLS}$, especially at very high redshift. In PH04, we argued that Péroux et al. (2003) had overstated the effect at $z > 3.5$ and underestimated the uncertainty. Our new results indicate the super-LLS contribute 20–50% to $\Omega_{g}^{H1}$ for the complete SDSS DR3 survey. Also, recall that the shape of $f_{H1}(N, X)$ is invariant with redshift (Fig. 7), therefore, it is likely that the Lyman limit systems offer a nonnegligible contribution to $\Omega_{g}^{H1}$ at all redshifts. To determine the value of $\Omega_{g}^{LLS}$ as a function of $f_{H1}$, we consider the relative evolution of $\ell_{LLS}$ and $\ell_{DLA}$. Current observations suggest that $\ell_{LLS}$ has a stronger redshift dependence than $\ell_{DLA}$. In fact, we do find $\Omega_{g}^{LLS}$ (as determined from the single power law fit to $f_{H1}^{DLA}$) to increase with redshift (Table 9). There is a comparable increase in $\Omega_{g}^{DLA}$, however, and the $\Omega_{g}^{LLS}/\Omega_{g}^{DLA}$ ratio is roughly constant in time.

We reemphasize that the value of $\Omega_{g}^{LLS}$ derived from the single power law fit to $f_{H1}^{LLS}$ is an underestimate of the true value. In Figure 12, we show a spline solution that matches the $f_{H1}(N, X)$ functional forms of the Lyα forest at $N_{H1} = 10^{15}$ cm$^{-2}$ and the damped Lyα systems at $N_{H1} = 2 \times 10^{20}$ cm$^{-2}$, and also gives the correct line density of Lyman limit systems. We can give an estimate of the LLS contribution based on this spline function, $\Omega_{g}^{LLS}/\Omega_{g}^{DLA} = 0.57$. Therefore, the likely contribution of the Lyman limit systems to $\Omega_{g}^{H1}$ is $\approx 50\% \Omega_{g}^{DLA}$, and they comprise $\approx 1/3$ of $\Omega_{g}^{H1}$. In § 6, we consider an alternate definition of the gas mass density: the mass density of gas that is predominantly neutral, $\Omega_{g}^{neu}$. Under this definition, one may disregard the majority of the Lyman limit systems on the grounds that they are highly ionized (Prochaska & Wolfe 1996; Prochaska 1999; Prochaska & Burles 1999; Dessauges-Zavadsky et al. 2003), but we suspect that at least a subset with $N_{H1} \approx 10^{20}$ cm$^{-2}$ is significantly

\begin{equation}
\int_{10^{10.3}}^{10^{17.2}} f_{H1}^{LLS} dN dX = \ell_{LLS} dX - \ell_{DLA} dX.
\end{equation}

To estimate $\ell_{LLS}(X)$, we adopt the functional form provided by Péroux et al. (2003) as a function of redshift, $\ell_{LLS}(z) = 0.07(1 + z)^{2.42}$, and adopt the mean value for the entire SDSS DR3 survey, i.e.,

\begin{equation}
\ell_{LLS}(X) = \int \ell_{LLS}(z) dX / \Delta X.
\end{equation}
neutral and could feed star formation. This neutral subset, however, may contribute only a few percent relative to $\Omega_g^{\text{cert}}$ and we contend that the damped Ly\(\alpha\) systems contain \(\gg 80\%\) of $\Omega_g^{\text{cert}}$ at high redshift. Until a robust determination of $f_{H_1}(N, X)$ and the ionization state of the gas in the Lyman limit systems is made, the only conservative practice is to restrict the discussion of $\Omega_H^1$ to include only those regions of the universe with surface density $N_{H_1} \geq 2 \times 10^{20} \text{ cm}^{-2}$ (i.e., $\Omega_{\text{LLS}}^1$). For the near future, this is the only quantity that will be precisely measured.

As an aside, consider the implications of the $\alpha_{\text{LLS}}$ value. First, this value is significantly shallower than the power-law dependence of the Ly\(\alpha\) forest. Second, it is shallower than the faint-end slope of the damped Ly\(\alpha\) $f_{H_1}(N, X)$ distribution. If we require that $f_{H_1}(N, X)$ and its first derivative are continuous across the Ly\(\alpha\) forest/LLS and LLS/DLA boundaries, then our results indicate that $f_{H_1}^\text{LLS}$ has an inflection with $d \log f_{H_1}^\text{LLS}/d \log N \sim -1$ (Fig. 12). It is not surprising that $f_{H_1}^\text{LLS}$ would have an unusual functional form, given that it spans the regime from highly ionized gas to primarily neutral gas. In fact, the inflection indicated by our analysis resembles the functional forms suggested by Zheng & Miralda-Escudé (2002) and Maller et al. (2003). In passing, we advertise that a principal goal of the MIKE/HIRES Lyman Limit Survey is to study $f_{H_1}^\text{LLS}$ and the ionization state of the Lyman limit systems (J. Prochaska et al., in preparation).

### 4.3.4. $\Omega_{\text{DLA}}^1$ Evolution

Let us consider the redshift evolution of $\Omega_{\text{DLA}}^1$ by evaluating equation (17) in a series of redshift intervals. Figure 13 presents the results. Following PH04, we estimate the uncertainty in $\Omega_{\text{DLA}}^1$ through a modified bootstrap technique. Specifically, we perform 5000 trials in which we randomly draw $p$ damped Ly\(\alpha\) systems from the observed sample, where $p$ is a normally distributed random number with mean equal to the number of damped systems in the interval ($m_{\text{DLA}}$) and with variance also equal to $m_{\text{DLA}}$. We calculate $\Omega_{\text{DLA}}^1$ for each trial and calculate the upper and lower values corresponding to 68.3% of the distribution.

---

**Table 9**

**Summary**

| $z$     | $dX$ | $m_{\text{DLA}}$ | $\log f_{H_1}(N, X)$ | $\Omega_{\text{DLA}}^1$ ($\times 10^{-3}$) | $\Omega_{\text{LLS}}^1$ ($\times 10^{-3}$) |
|---------|------|------------------|-----------------------|---------------------------------------------|---------------------------------------------|
| [2.2, 2.5] | 205.7 42.7 205.7 92 | $-21.73 \pm 0.04$ | $-23.21 \pm 0.05$ | $-24.14 \pm 0.10$ | $0.072 \pm 0.003$ |
| [2.5, 3.0] | 208.7 42.7 208.7 92 | $-21.84 \pm 0.06$ | $-23.69 \pm 0.15$ | $-24.36 \pm 0.22$ | $0.053 \pm 0.005$ |
| [3.0, 3.5] | 210.6 42.7 210.6 92 | $-22.18 \pm 0.07$ | $-24.16 \pm 0.17$ | $-24.42 \pm 0.26$ | $0.071 \pm 0.006$ |
| [3.5, 4.0] | 212.6 42.7 212.6 92 | $-22.52 \pm 0.09$ | $-24.51 \pm 0.21$ | $-24.70 \pm 0.32$ | $0.051 \pm 0.007$ |
| [4.0, 4.5] | 214.6 42.7 214.6 92 | $-22.87 \pm 0.10$ | $-24.89 \pm 0.35$ | $-25.03 \pm 0.45$ | $0.074 \pm 0.008$ |
| [4.5, 5.0] | 216.6 42.7 216.6 92 | $-23.23 \pm 0.10$ | $-25.22 \pm 0.49$ | $-25.22 \pm 0.59$ | $0.074 \pm 0.009$ |
| [5.0, 5.5] | 218.6 42.7 218.6 92 | $-23.69 \pm 0.11$ | $-25.61 \pm 0.64$ | $-25.61 \pm 0.74$ | $0.074 \pm 0.010$ |

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**Figure 12**—Figure depicting the $f_{H_1}(N, X)$ distribution of the quasar absorption line systems at $z=2.7$. The distribution for the damped Ly\(\alpha\) systems corresponds to the $\Gamma$ function fit to the SDSS DR3.4 sample. The distribution for the Ly\(\alpha\) forest ($N_{H_1} < 10^{20} \text{ cm}^{-2}$) is taken from Kirkman & Tytler (1997) scaled to the $\Lambda$CDM cosmology. We show three curves for the Lyman limit system regime, which should only be considered as a sketch: (1) the dotted curve is the single power law fit to $f_{H_1}^\text{LLS}$ constrained to match the incidence of Lyman limit systems at $z \sim 2.7$; (2) the dashed curve is a spline function constrained to match the Ly\(\alpha\) forest and damped Ly\(\alpha\) systems, which clearly overpredicts the incidence of Lyman limit systems; and (3) the solid curve is a spline function fit to the Ly\(\alpha\) forest and damped Ly\(\alpha\) systems, also constrained by a single point at $N_{H_1} = 10^{21} \text{ cm}^{-2}$ defined such that the integral constraint for the Lyman limit systems is satisfied. [See the electronic edition of the Journal for a color version of this figure.]

**Figure 13**—Neutral gas mass density of the damped Ly\(\alpha\) systems alone as a function of redshift. There is an increase of approximately a factor of 2 in $\Omega_{\text{DLA}}^1$ from $z=2$ to 3, with the majority of rise occurring in only 500 Myr. Note the data point at $z < 2.2$ (marked with a cross) does not include measurements from the SDSS survey.
The results presented in Figure 13 provide the first statistically significant evidence that $\Omega^{\text{DLA}}_g$ evolves with redshift. Comparing the measurements in the $z = [2.2, 2.5]$ and $z = [3.0, 3.5]$ intervals, we find a $50\% \pm 10\\%$ decrease in the lowest SDSS redshift bin. This evolution occurs during the same time interval at which the decrease in $f^{\text{DLA}}_{\text{Ly} \alpha}(X)$ is observed (Fig. 8). Regarding the line density, we have attributed the decline to a decrease in the typical cross section of the damped Ly$\alpha$ systems. Given the decrease in $\Omega^{\text{DLA}}_g$, it is evident that the gas is not simply contracting into smaller structures (e.g., via dissipative cooling), but is being consumed and/or expelled from the system.

Contrary to previous claims, we find no evidence for evolution in $\Omega^{\text{DLA}}_g$ at $z > 3.5$, although a modest increase (or decrease) is permitted by the observations. Similarly, the results at $z \approx 2$ from previous work (albeit uncomfortably high$^8$) are consistent with the $z = 2.3$ data point. We also caution the reader that the results at $z > 4$ should be confirmed by higher resolution observations. At these redshifts, blending in the Ly$\alpha$ forest is severe, and we worry that the SDSS spectroscopic resolution is insufficient. In passing, we also note that a significant contribution to $\Omega^{\text{DLA}}_g$ at $z > 4$ comes along the single sight line to J162626.5+275132, which shows two $N_{\text{HI}} \approx 10^{21}$ cm$^{-2}$ damped Ly$\alpha$ systems at $z \approx 5$ and even two additional systems with comparable $N_{\text{HI}}$ values at $z \sim 4.5$, which are not in the statistical sample.

4.4. Summary

Table 9 presents a summary of $f^X_{\text{HI}}(N, X)$ and its zeroth and first moments for a series of redshift intervals. A qualitative summary of the new results is that they are in broad agreement with the previous analyses based on substantially smaller data sets (Wolfe et al. 1995; Storrie-Lombardi & Wolfe 2000; Péroux et al. 2003). With the increased sample size, however, we have measured evolution in the incidence and H$\iota$ content of these galaxies at $z > 2$ to unprecedented precision.

5. SYSTEMATIC EFFECTS

With the large sample size of the SDSS DR3, we now have sufficient signal to examine a number of systematic effects on the results of our analysis. This section describes an investigation into a few of these effects. It is advantageous that the entire SDSS sample was observed with the same instrument, reduced with the same software, and analyzed by one group. In contrast, the compilation of Péroux et al. (2003) is based on many surveys carried out on over 10 telescopes and reduced and analyzed by at least five different individuals. This undoubtedly leads to at least minor systematic differences in the surveys, e.g., differences in the continuum placement, systematic effects related to instrumental resolution, and/or color selection of the quasar populations. Of course, if multiple groups report the same value, this lends confidence to the sets of procedures related to damped Ly$\alpha$ surveys.

5.1. S/N$_{\text{lim}}$ and Color Selection

All of the results presented in this paper are based on searches for damped Ly$\alpha$ systems in the spectral regions of quasars where

\footnote{Note that the value for $\Omega^{\text{DLA}}_g$ is reduced by \approx 50$\% if one removes the single damped system at $z = 2.04$ toward Q0458–02. This stresses the sensitivity of these low-redshift results to small-number statistics (as stressed by Chen et al. 2005), and the bootstrap error estimate may be overly optimistic in this case. Coincidentally, Q0458–02 is an optically variable quasar which in its low state has a magnitude below the original survey detection limit. Also note that this redshift interval does not include any data from the SDSS survey.}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure14.eps}
\caption{Top: Line density as a function of redshift for the various sample cuts on S/N$_{\text{lim}}$ and color selection criteria listed in Table 2. The data are plotted relative to the SDSS DR3.4 sample and are offset in redshift for presentation purposes only. The values are calculated in the redshift intervals $z = [2.2, 2.5], [2.5, 3.0], [3.0, 3.5], [3.5, 4.4]$. Bottom: Results for $\Omega^{\text{DLA}}_g$ for the same cuts and also relative to SDSS DR3.4. There is very little apparent difference between the various samples.}
\end{figure}

the median S/N exceeds 4 in a 20 pixel bin (§ 2). Our experience via visual inspection and Monte Carlo simulations is that this limit is just satisfactory. Lowering the limit to a S/N$_{\text{lim}} = 3$ gives many more false positives and a greater number of missed damped Ly$\alpha$ systems. Of course, it is important to test the sensitivity of our results to S/N$_{\text{lim}}$. Figure 14a presents the line density $f^{\text{DLA}}_{\text{Ly} \alpha}(X)$, and Figure 14b the neutral gas mass density $\Omega^{\text{DLA}}_g$ relative to the full sample as a function of redshift for several values of S/N$_{\text{lim}}$. A similar analysis was performed for the samples restricted to the strict color criteria (Richards et al. 2002). See Table 2 for a description of each cut of the SDSS DR3.

Examing these figures, we find little difference between the various samples, and therefore find no systematic bias related to S/N$_{\text{lim}}$ or the color-selection criteria. In fact, the scatter in the data is smaller than that expected for a Poissonian distribution. This is because the samples are not independent. Nevertheless, this analysis demonstrates that our results are relatively insensitive to S/N$_{\text{lim}}$ and the color-selection criteria.

5.2. Quasar Magnitude and S/N

There are a number of reasons to examine the results as a function of the quasar magnitude and/or the S/N of its spectrum. These include considerations of dust obscuration (Fall & Pei 1993), the precision of the $N_{\text{HI}}$ values as a function of S/N, and gravitational lensing. We consider the quasar magnitude and spectral S/N together because we have found a similar dependence on the results for these two characteristics. Although there is not a strict one-to-one relationship between quasar magnitude and S/N for the SDSS survey, the two characteristics are closely associated.

We have calculated the magnitude of the quasar as follows. First, we identify the Sloan filter closest to $\lambda = (1 + z_{\text{QSO}})1325$ Å.
Second, we adopt the PSF magnitude for the quasar as reported in SDSS DR3. Third, we flux calibrate the one-dimensional quasar spectrum assuming that its relative flux is accurate. Finally, we calculate the median flux in the interval $\lambda_{\text{rest}} = 1300–1350$ Å (which avoids strong emission-line features) and convert to AB magnitude. To estimate the S/N of the spectrum, we calculate the median S/N for $\lambda_{\text{rest}} = 1440–1490$ Å, where $z_{\text{QSO}} < 5$ and $\lambda_{\text{rest}} = 1287–1366$ Å for $z_{\text{QSO}} > 5$. Figure 15 plots the quasar magnitude versus the spectral S/N. There is a reasonably tight correlation, with a few outliers, which are primarily exotic BAL quasars.

The upper panel of Figure 16 presents the line density of damped Ly$\alpha$ systems as a function of redshift for three cuts of the SDSS DR3_4 sample: (1) the complete sample; (2) the brightest 33% of the quasars; and (3) the faintest 33% of the quasars. Note that there is no significant dependence of $f_{\text{DLA}}$ on quasar magnitude. The lower panel shows the same quantity for cuts on the S/N. Note that the median magnitudes of the bright and faint samples for the lowest redshift bin are 18.4 and 19.5 mag, respectively. This difference in magnitudes is significant, and it nearly brackets the “break magnitude” of the quasar luminosity function at $z = 2$ (Boyle et al. 2000). The results indicate that if dust obscuration is relevant to damped Ly$\alpha$ surveys, then the line density is insensitive to its effects. While the line density may not be very sensitive to dust obscuration, it is possible that our results violate the predictions of Fall & Pei (1993). A quantitative statement awaits a full treatment that includes the SDSS quasar color-selection criteria (M. T. Murphy et al., in preparation).

In contrast, we do find a systematic relationship between quasar magnitude (and S/N) with $\Omega_g^{\text{DLA}}$. Figure 17 presents the results for the same cuts of SDSS DR3_4 as in Figure 16. It is evident that the bright subsample shows systematically higher $\Omega_g^{\text{DLA}}$ values than the faint subsample. Of course, in order to explain the independence of $f_{\text{DLA}}$ to quasar magnitude, all of the difference in $\Omega_g^{\text{DLA}}$ must arise from the frequency of large $N_{\text{HI}}$, damped systems. Indeed, Figure 18 shows that the $f_{\text{HI}}(N, X)$ distributions are comparable for the bright and faint subsamples for $N_{\text{HI}} < 10^{21}$ cm$^{-2}$, but there is a factor of 5 difference in the incidence of systems with $N_{\text{HI}} > 10^{21.4}$ cm$^{-2}$. This has the greatest impact on the $\Omega_g^{\text{DLA}}$ results, which we now discuss.

Let us consider some possible explanations for the results in Figures 17 and 18:
1. Chance (small-number statistics).—In any given redshift interval in Figure 17, the results are significant at only the ≈1 σ level. Taken together, however, the effect is significant at greater than the 95% c.l.; the weighted mean of the ratio of the bright to faint subsamples is \( \Omega^\text{DLA} \text{(bright)} / \Omega^\text{DLA} \text{(faint)} = 1.4 \pm 0.2 \). Therefore, we consider it unlikely that the effect is related only to statistical fluctuations.

2. DLAs are intrinsic to the quasar.—This is a difficult assertion to disprove. Figure 19 plots a histogram of the relative separation of the damped Lyα systems from the quasar,

\[
\delta_{\text{rel}} = \frac{z_f - z_{\text{DLA}}}{z_f - z_i},
\]

restricted to sight lines where \( z_f - z_i > 0.2 \). While there are fewer systems with \( z_{\text{DLA}} \approx z_i \), this is expected because the incidence of the damped Lyα systems increases with redshift. At present, we do not consider association with the quasar to be an important issue.

3. The survey has missed damped Lyα systems with large \( N_{\text{H}_1} \), toward faint quasars.—Given that our algorithm is most sensitive to spectral regions of very low S/N, it is very unlikely that we would miss a damped Lyα system whose core is much larger than the search window \( 6(1+z) \) Å. Furthermore, the profiles with very large \( N_{\text{H}_1} \) values are the easiest to identify, and we would have recovered most in our visual inspection of the spectra. Finally, these systems will probably all show significant metal-line absorption, and we would have identified them independently of the Lyα profile (e.g., § 5.4).

There is, however, one bias related to this point. If a damped Lyα profile coincides with the wavelength \( \lambda_i \) in the quasar spectrum where the median S/N would have otherwise exceeded \( S/N_{\text{lim}} \) (see § 2), then the presence of a damped Lyα system would preclude its inclusion in the statistical sample (and possibly its discovery altogether). That is, the presence of a damped Lyα profile at wavelength \( \lambda_{\text{DLA}} \), where the median S/N of the unabsorbed flux exceeds 4, lowers the S/N at \( \lambda_{\text{DLA}} \), such that \( \lambda_i \) occurs redward of the damped Lyα system. This is true for damped Lyα systems of all \( N_{\text{H}_1} \) values, although the effect will be greatest for larger \( N_{\text{H}_1} \). We have accounted for this bias, in part, by defining \( z_1 \) to be 1000 km s\(^{-1}\) redward of the redshift corresponding to \( \lambda_i \). Nevertheless, this is an important issue.

4. Overestimating \( N_{\text{H}_1} \), in the bright sample.—We have examined the damped Lyα profiles for every system with \( N_{\text{H}_1} > 10^{21.4} \) cm\(^{-2}\). In no case would we modify the best \( N_{\text{H}_1} \) value beyond the reported uncertainty. Furthermore, the bright sample has the highest S/N data, and we consider the \( N_{\text{H}_1} \) values to be well constrained. All have associated metal-line absorption and are reasonably well determined quasar continua. Therefore, we consider this explanation to be unimportant.

5. Underestimating \( N_{\text{H}_1} \), in the faint sample.—Because these quasars are faint, the spectra have lower S/N and more uncertain \( N_{\text{H}_1} \) values. While this could lead to a significant underestimate of \( N_{\text{H}_1} \), several effects work against it. First, \( f_{\text{HL}}(N, X) \) is sufficiently steep (particularly at high \( N_{\text{H}_1} \) ) that a Malquist bias will actually lead to a flattening of \( f_{\text{HL}}(N, X) \) at the high \( N_{\text{H}_1} \) end. This leads to an overestimate of \( \Omega^\text{DLA} \) in the faint subset, because the bias will be more significant for \( N_{\text{H}_1} \) values with larger uncertainty. Second, the effects of low S/N are most significant at low \( N_{\text{H}_1} \) values, where only a handful of pixels may constrain the result. But these systems do not contribute significantly to \( \Omega^\text{DLA} \).

Third, at large \( N_{\text{H}_1} \) values, the profile extends over \( \approx 100 \) Å and is generally constrained by tens of pixels. It is true that uncertainty in the continuum level is greater, but we do not believe this to be the problem.

To further pursue the possibility that we have underestimated \( N_{\text{H}_1} \) in the faint subsample, we reexamined every Lyα profile with \( N_{\text{H}_1} > 10^{21} \) cm\(^{-2}\) in the \( z \sim 2.7 \) redshift bin. While we could allow for 0.1–0.2 dex larger values in a number of cases, this would not account for the differences in \( \Omega^\text{DLA} \). Furthermore, we note that the \( f_{\text{HL}}(N, X) \) value in the \( N_{\text{H}_1} \) interval \( 10^{21} – 10^{21.4} \) cm\(^{-2}\) is lower in the faint subsample. Therefore, it would require a systematic underestimate in \( N_{\text{H}_1} \) at nearly all values to explain the observations. At present, we consider an underestimate of \( N_{\text{H}_1} \) values in lower S/N data to be a possible contribution to the differences in \( \Omega^\text{DLA} \), but unlikely to be the main explanation.

6. Dust obscuration.—To date, every damped Lyα system observed at high resolution has a measured metallicity exceeding...
1/1000 solar (Prochaska et al. 2003a). With the presence of metals, there is the prospect that the gas has a nonnegligible dust content (e.g., Pettini et al. 1994). Indeed, damped Ly\(\alpha\) systems with metallicity >1/10 solar have enhanced Si/Fe ratios that are best explained by differential depletion (Prochaska 2003). As Ostriker & Heisler (1984) first noted, the damped Ly\(\alpha\) systems with the highest optical depths of dust will obscure the background quasar and possibly remove it from a magnitude-limited quasar survey.

The prediction, as formalized by Fall & Pei (1993), is that optical quasar samples will underestimate \(\Omega_{DLA}^g\) owing to this bias. As Ellison et al. (2004) have stressed, the effect will be less significant if the quasar survey extends beyond the peak in the luminosity function. In any case, this bias implies that the \(\Omega_{DLA}^g\) values from brighter quasars should be lower than the value inferred from faint quasars. We observe the opposite trend in Figure 17. Therefore, the results are unlikely to be explained by dust obscuration.

7. Gravitational lensing.—If the damped Ly\(\alpha\) systems arise in massive halos or disks, then it is possible that they would gravitationally magnify the background quasar (Bartelmann & Loeb 1996; Smette et al. 1997; Maller et al. 1997). In their analysis of the SDSS DR2 quasar database, Murphy & Liske (2004) reported an approximately 2 \(\sigma\) result that the luminosity function of quasars with foreground damped Ly\(\alpha\) systems is brighter than those without. Unlike dust obscuration, this systematic effect could explain the results in Figure 17. In fact, treatments based on describing damped Ly\(\alpha\) systems as exponential disks predict that the effect will be greatest for damped Ly\(\alpha\) systems with large \(N_{H_1}\) values (Bartelmann & Loeb 1996; Maller et al. 1997).

At present, we believe gravitational lensing to be the most plausible explanation for the results in Figures 17 and 18. The key implications for \(\Omega_{DLA}^g\) are that (i) our reported values may be too high, and (ii) the evolution of \(\Omega_{DLA}^g\) revealed by the entire sample is qualitatively correct. Therefore, while this systematic effect is important, our conclusions are relatively invariant to it. We note, however, that the effect should be even more pronounced at \(z < 2\) and may significantly affect damped Ly\(\alpha\) statistics at these redshifts (Rao & Turnshek 2000). If gravitational lensing does explain the effect, it may allow for a statistical mass measurement of at least the high-\(N_{H_1}\) sight lines. It also motivates a high spatial resolution survey of all damped Ly\(\alpha\) systems with \(N_{H_1} > 10^{21}\) cm\(^{-2}\). In a future paper (M. T. Murphy et al. 2005, in preparation) we will present a full analysis of gravitational lensing and dust obscuration for the SDSS DR3 sample.

5.3. Human Error

There is a nonnegligible likelihood that we have overlooked a few systems or have made significant errors in a few select systems. Regarding PH04, for example, we note an incorrect \(N_{H_1}\) value for the damped system at \(z = 2.77\) toward J084407.29+515311 (§ 3.3) and also a bug in our calculation of \(f(z)\) for the SDSS DR1 sample. To quickly disseminate corrected and updated results to the community, we have established a public Web site where all of the fits and analysis will be presented.\(^9\) We encourage the community to report any mistakes in our analysis to the lead author via the e-mail address ssdsdlau@ucolick.org.

5.4. Unusual Systematic Effects: “Things that Go Bump in the Night”

With a sample of damped Ly\(\alpha\) systems approaching 1000, it is not surprising that unexpected systematic errors will arise. Figure 20 presents the Ly\(\alpha\) profile and metal-line profiles for the damped Ly\(\alpha\) candidate at \(z = 2.42\) toward J130634.6+523250. This damped Ly\(\alpha\) candidate was not identified by our automated algorithm because of significant flux at the center of the Ly\(\alpha\) profile. Instead, the system was identified because of its metal-line absorption, and we immediately hypothesized that the flux in the Ly\(\alpha\) profile was due to Ly\(\alpha\) emission from the host galaxy. The emission line would be amazingly strong, however, and we

\(^9\) See http://www.ucolick.org/~xavier/SDSSDLA/index.html.
considered alternate explanations. In time, we realized that the feature is an emission line: [O ii] emission from a z = 0.116 galaxy that lies within the 3rd SDSS fiber. Emission lines of Hα, Hβ, and [O iii] are also apparent in the quasar spectrum. Ignoring the [O ii] emission, we have fit the Lyα profile, and its central value places it beneath the statistical threshold for damped Lyα systems. Nevertheless, this is a systematic effect that leads to an underestimate of f_HI(N, X) at all N_HI values. It is difficult to quantify the overall effect here, but it is presumably less than 1%.

6. DISCUSSION AND SPECULATIONS

The emphasis of this paper is on describing the results of the damped Lyα survey of the SDSS DR3 quasar database. These results and a discussion of the systematic errors have been presented in preceding sections. We now consider a few of the implications, with an emphasis on the new results. We also compare the observations to theoretical treatments of the damped Lyα systems within ΛCDM models of galaxy formation. We consider the results from the smooth particle hydrodynamic (SPH) simulations of Nagamine et al. (2004), the Eulerian simulations of Cen et al. (2003), and the semianalytic model (SAM) of the Santa Cruz group (Somerville et al. 2001; Maller et al. 2001, 2003). It is important to stress that each model includes its own set of star formation and feedback recipes, which do bear on the results for the damped Lyα systems.

Consider first the N_HI frequency distribution, f(HI)(N, X). Perhaps the most remarkable result from the SDSS DR3 sample is that there is no statistical evidence for any evolution in the shape of f(HI)(N, X) with redshift (Fig. 7). There is, however, evidence for evolution in the normalization of f(HI)(N, X) as traced by the trends in the zeroth and first moments of the distribution function. These results suggest that the gas distribution within galaxies is similar at all redshifts and that only the number and/or sizes of these galaxies evolve significantly. Another interesting result is that the faint-end slope of the f(HI)(N, X) distribution is α_HI ≈ −1.8. This slope matches the faint-end slope of the dark matter halo mass function for cold dark matter (CDM; e.g., Sheth et al. 2001). If this is not a coincidence, it indicates that low-mass halos dominate the incidence of damped Lyα systems at low N_HI values. Furthermore, it suggests that the cross section A(X) of low-mass galaxies is nearly independent of mass. At present, however, we consider the correspondence to be a coincidence.

A comparison of the results with ΛCDM models of galaxy formation is presented in Figure 21 at z = 3 and 4. The f(HI)(N, X) curves for the SPH simulations of Nagamine et al. (2004) and the SAM model of Maller et al. (2001). The SAM model shows a reasonable match to the shape of f(HI)(N, X) at z = 3, yet systematically underpredicts the observations. Maller et al. (2001) were primarily interested in modeling the kinematics of the damped Lyα systems, and we suspect that their results are insensitive to the normalization of f(HI)(N, X). Nevertheless, the discrepancy suggests that the SAM model has too few damped Lyα systems at z = 3. Similarly, the SPH theoretical curves offer a reasonable match to the observations at large N_HI value, yet significantly underpredict f(HI)(N, X) at low N_HI values.

The discrepancy has several important implications. First, the SPH simulations will predict a significantly smaller contribution to Ω_HI for the Lyman limit systems at these redshifts. In part, this is a restatement of a current problem in numerical cosmology: the simulations underpredict the incidence of Lyman limit systems by an order of magnitude (Gardner et al. 2001). Second, we reemphasize the critical constraint imposed by two sets of observations of the damped Lyα systems: (1) f(HI)(N, X) and (2) the velocity width distribution of the low-ion profiles (Prochaska & Wolfe 1997). Jedamzik & Prochaska (1998) first emphasized that there is a tension between f(HI)(N, X) and the velocity width distribution. Specifically, if one introduces enough low-mass halos to match the low N_HI end of f(HI)(N, X), this implies far too many damped Lyα systems with small velocity width. If the SPH simulations were modified to match the f(HI)(N, X) observations (e.g., via different treatments of feedback or radiative transfer), we predict that (1) the dependence of the cross section A(X) on the halo mass as reported by Nagamine et al. (2004) would change significantly, and (2) the simulations would not reproduce the damped Lyα kinematics. We also note that the results of Nagamine et al. (2004) show that f(HI)(N, X) is relatively insensitive to treatments of feedback. It is possible that f(HI)(N, X) and the damped Lyα kinematics present a fundamental challenge to scenarios of galaxy formation within the ΛCDM cosmology.

Now consider the evolution in the line density of damped Lyα systems. Because σ_DLAX is the product of the comoving number density and cross section of damped Lyα systems (eq. [14]), the rise in σ_DLAX reflects an increase in one or both of these quantities. We can estimate the evolution in σ_DLAX by considering the Press-Schechter formalism for the mass function of dark matter halos (e.g., Peacock 1999). Within this formalism one can define a mass scale M, as a function of redshift, which identifies the typical mass of assembly. At z = 3 in the ΔCDM cosmology with σ_9 = 1, M0 ≈ 10^{10} M⊙. Halos with masses M > M0 will have a number density that increases significantly from z = 3 to 2. Therefore, damped Lyα systems are unlikely to arise in halos with M > 10^{10} M⊙ at these redshifts. Furthermore, although halos with M < M0 do have a decreasing comoving number density, the decrease is small (i.e., <15% for M = 10^9 M⊙). Within the context of hierarchical cosmology, therefore, the most likely explanation for the decrease in σ_DLAX is a corresponding decline in A(X). There are several physical effects that could reduce A(X),
the mass density of Irr galaxies (theoretical curves of Cen et al. (2003; EULER; from S. M. Rao et al. (in preparation). These observations are compared to the

tend that one or more feedback mechanisms have significantly
believed to be roughly constant (e.g., Haardt & Madau 1996),
the intensity of the extragalactic background radiation field is
but probably cannot account for the bulk of evolution. Similarly,
blue line
red
SAMS;
red

Our analysis (Fig. 22, including recent results (purple)
from S. M. Rao, D. A. Turnshek, & D. Nestor (in preparation) compared to several ΛCDM models, and also current estimates of the mass density of stars (star), neutral gas (diamond), and Irr galaxies (plus signs) at z = 0. It is important to note that the theoretical models of Somerville et al. and Nagamine et al. include contributions to Ωg from all quasar absorption-line systems (i.e., they calculate ΩgH,1), whereas the observational measurements are restricted to the damped Lyα systems. Therefore, if the Lyman limit systems do contribute significantly to ΩgH,1, we must increment the observations accordingly. Alternatively, we recommend that future theoretical analysis be restricted to sight lines with NHI ≥ 2 × 1020 cm−2 (e.g., Cen et al. 2003).

Examining the damped Lyα observations alone, we note a relatively confusing picture. While the results based primarily on the SDSS DR3 observations (z > 2.2) show a well-behaved trend with redshift, the estimates of ΩgDLA at z < 2 are all consistent with one another, with a central value higher than the z = 2.3 measurement. While each individual measurement at z < 2 is consistent with the SDSS data point at z = 2.3, taken together the difference is significant, at >95% c.l. In fact, if one were to ignore the redshift interval at z = 2.3, the observations are consistent with no evolution in ΩgDLA from z = 0.1 to 4.5. Before reaching such a conclusion, however, we wish to emphasize several points: (1) the value in the z = [2.2, 2.5] interval is very well determined because it is based on ~100 damped Lyα systems; (2) the z ∼ 2 data point is derived from a heterogeneous sample of observations and is dominated by a single damped Lyα sys-

Fig. 22.—Gas mass density of neutral gas for the damped Lyα systems from our analysis (z > 1.5 with SDSS restricted to z > 2.2) and recent results (purple) from S. M. Rao et al. (in preparation). These observations are compared to the theoretical curves of Cen et al. (2003; EULER; SAMs; red), and Nagamine et al. (2004; SPH; dotted blue line, D5 model; solid blue line, Q5 model). The data points at z = 0 correspond to the stellar mass density from Cole et al. (2001; star), the neutral gas mass density (diamond), and the mass density of Irr galaxies (plus signs; Fukugita et al. 1998).

tem; (3) the low-redshift values are based on the novel yet non-
standard technique of Rao & Turnshek (2000), whose approach has its own set of systematic errors which are uniquely different from the damped Lyα survey described in this paper; and (4) we argue in § 5.2 that the ΩgDLA results may be biased by gravitational lensing. If this is confirmed, the effect should be largest at z < 2. These points aside, it is clear that achieving better than 10% precision on ΩgDLA at z < 2 is a critical goal of future damped Lyα surveys. At z ∼ 2, this will require a large observing campaign with a spectrometer efficient down to 3200 Å. At lower redshift, it will require a new UV space observatory.

Comparing the models, we note a wide range of predictions. The most successful models at z > 2 are from Nagamine et al. (2004), in particular their D5 run. This model reproduces both the shape and normalization of the observed data. In contrast, the Eulerian and SAM models overpredict ΩgDLA at all redshifts and at z < 3, respectively, even if one adopts a 1.5 multiplicative correction due to the Lyman limit systems. Because the cooling processes and timescales are comparable in all of the models (e.g., Pearce et al. 2001), the differences must be due to processes that consume or ionize the neutral gas (e.g., star formation, galactic winds, or AGN feedback). The indication from our observations is that the Eulerian and SAM models underpredict these processes at z ≥ 2 and therefore overestimate Ωg.

Now consider a comparison of the high-z ΩgDLA values with the mass density at z = 0 of stars Ω*, neutral gas Ωg21 cent, and dwarf galaxies Ωg. The stellar mass density was estimated by Cole et al. (2001) from an analysis of the Two Degree Field (2dF) survey. The uncertainty in this estimate is dominated by systematic error related to the assumed initial mass function. Wolfe et al. (1995) first stressed that the gas mass density of the damped Lyα systems is comparable to Ω*. Adopting the ΛCDM cosmology and the current estimate of Ω*, we now find that Ω*, exceeds ΩgDLA by a factor of 2–3 at 3 = 3. However, because star formation is ongoing at all redshifts probed by the damped Lyα systems (e.g., Chen & Lanzetta 2003; Wolfe et al. 2003b; Møller et al. 2002), it would be wrong to interpret the maximum ΩgDLA value as the total gas mass density contributed by the damped Lyα systems. It is more accurate to regard damped Lyα systems as neutral gas reservoirs in which gas consumed by star formation is replaced by neutral gas accreted from the intergalactic medium (IGM). In this manner, the mass density of damped Lyα systems would be less than Ω*, at any given epoch. Therefore, it is reasonable to assume that all of the stars observed today arose from gas originating in the damped Lyα systems. Indeed, this is the generic conclusion of current cosmological simulations. These points aside, it is evident that the damped Lyα systems contain sufficient gas mass to account for all of the stars observed in disks today, provided that current estimates are correct (Ωdisk ∼ Ω*/3; Fukugita et al. 1998).

Examining Figure 22, we note that the difference between Ω21 cent at z = 0 and ΩgDLA at z = 2.3 is 0.15 ± 0.08, i.e., consistent with very little evolution if one ignores the results at z ∼ 1 we present from S. M. Rao et al. (in preparation). Is this a remarkable coincidence or is there a physical explanation (e.g., the gas accretion rate equaled the star formation rate over the past 10 Gyr)? Before addressing this question, consider the determination of Ω21 cent. The value is derived from large-area surveys of 21 cm emission-line observations for H i clouds. The most recent results are from the HIPASS survey, as analyzed by Zwaan et al. (2005). The analysis proceeds by fitting a functional form (a η function) to the H i mass distribution of all galaxies detected. The Ω21 cent value is simply proportional to the first moment of this distribution function. The key point to emphasize is that the
analysis includes all H I gas within the beam of HIPASS, i.e., the values are independent of H I surface density and are not restricted to the damped Lyα threshold. In the extreme case that the H I gas is predominantly distributed in Mestel disks with $\Sigma(R) \propto R^{-1}$, the contribution to $\Omega_{\gamma}^{21}$ from damped Lyα systems is $\Omega_{\gamma}^{21} = \Sigma_{\text{trunc}}/\Omega_{\text{DLA}} = N_{\text{trunc}}/10^{20.5} \text{ cm}^{-2}$, where $\Sigma_{\text{trunc}}$ and $N_{\text{trunc}}$ are the surface density and H I column density, respectively, at the truncation radius of the Mestel disk, and $\Omega_{\text{DLA}}$ is the surface density at the damped Lyα threshold. One can adopt a truncation radius for the Mestel disk according to the photoionization edge set by the intensity of the extragalactic UV background (EUVB) or observational constraints (e.g., Maloney 1993). Adopting a relatively conservative value of $N_{\text{trunc}} = 10^{19.5} \text{ cm}^{-2}$, we find $\Omega_{\gamma}^{21} = 0.15\Omega_{\gamma}^{21}$. Of course, this is a somewhat extreme model, because many gas disks have exponential profiles. For an exponential disk, the value of $\Omega_{\gamma}^{21}/\Omega_{\gamma}^{21}$ is sensitive to the ratio of the radii corresponding to the damped Lyα threshold and the exponential scale length. Taking $R_{\text{DLA}}/R_{\text{exp}} = 2$, we find $\Omega_{\gamma}^{21} = 0.5\Omega_{\gamma}^{21}$. These simple estimates imply that a significant fraction of $\Omega_{\gamma}^{21}$ at $z = 0$ could come from Lyman limit systems.

One can also place an empirical constraint on $\Omega_{\gamma}^{21}/\Omega_{H}$ from the H I distribution function at $z = 0$ as measured by Ryan-Weber et al. (2003). If one adopts their double power law fit to $f_{\text{HI}}(N, X)$ with exponents $\alpha_3 = -1.4$ and $\alpha_4 = -2.1$ and $N_{\text{HI}} = 10^{20.5} \text{ cm}^{-2}$, extrapolates this frequency distribution to $N_{\text{trunc}} = 10^{19} \text{ cm}^{-2}$, and integrates to $N_{\text{trunc}} = 10^{21.6} \text{ cm}^{-2}$ (the largest $N_{\text{HI}}$ value measured), we find $\Omega_{\gamma}^{21} = 0.6\Omega_{\gamma}^{21}$. There is significant uncertainty and degeneracy in the fitted parameters of $f_{\text{HI}}(N, X)$, however, and $\Omega_{\gamma}^{21}/\Omega_{H}$ could be significantly higher or lower. Nevertheless, it is our present view that $\Omega_{\gamma}^{21}$ at $z = 0$ is $\approx 0.5\Omega_{\gamma}$. Therefore, we argue that a strict comparison of $\Omega_{\gamma}^{21}$ at $z = 0$ and $z = 2$ could imply a decrease in $\Omega_{\gamma}^{21}$ over the past 10 Gyr.

Given the uncertainties inherent to $\Omega_{H}^{21}$ and the fact that it has an ambiguous physical meaning, we now advocate an alternate definition for $\Omega_{H}$, motivated by star formation processes. Define $\Omega_{\text{neut}}$ to be the mass density of gas that is predominantly neutral. Under this definition, $\Omega_{\text{neut}}$ evolves as follows. The decrease of the EUVB intensity with decreasing redshift implies that lower surface densities will be neutral at lower redshift. Therefore, it is very possible that $\Omega_{\text{neut}}$ is equal to $\Omega_{\gamma}^{21}$ at $z = 2$ and the HIPASS value at $z = 0$. In this case, the gas reservoir available to star formation may have remained nearly constant over the past 10 Gyr (subject, of course, to the value of $\Omega_{\text{neut}}$ from $z = 0$ to 2).

We emphasize that this is consistent with the presence of star formation, provided gas replenishment from the IGM is available. Future progress on these issues will require an accurate determination of $f_{\text{LLS}}^{21}$ at all redshifts and also an accurate assessment of the ionization state of the gas as a function of H I column density.

Finally, compare $\Omega_{\gamma}^{21}$ at $z = 3$ to the mass density in dwarf galaxies $\Omega_{H}$ as derived by Fukugita et al. (1998). The value presented here is their estimate for the stellar mass density in Irr galaxies, boosted by a factor of 2 to account for the gas mass and by 30% for $H_{0} = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We emphasize that the value of $\Omega_{H}$ is difficult to estimate and may be more uncertain than depicted here. Nevertheless, it is evident that the mass density of dwarf galaxies is roughly 10 times smaller than $\Omega_{\gamma}^{21}$ at $z = 3$. A number of authors have argued that the majority of damped Lyα systems will evolve into dwarf galaxies today. It is obvious, however, that the majority of damped Lyα systems (by mass) cannot evolve into dwarf galaxies. And because damped Lyα systems with all values of $N_{\text{HI}}$, contribute to $\Omega_{\gamma}^{21}$ (Fig. 10), we argue that the damped Lyα systems by number are not the progenitors of dwarf galaxies. As we have argued previously, it is premature to interpret the observed abundance patterns as significant evidence for a link between damped Lyα systems and dwarf galaxies (Prochaska 2003). Furthermore, the kinematic characteristics of the damped Lyα systems preclude such an interpretation (Prochaska & Wolfe 1997; Prochaska et al. 2002). Revealing the true nature of the damped Lyα systems, of course, will require detailed follow-up studies (high-resolution spectroscopy, deep imaging, etc.) of the galaxies identified in this survey.

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