The hydrogen content of the universe over the past 10 Gyr

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Abstract

We use the Hubble Space Telescope (HST) archive of ultraviolet (UV) quasar spectroscopy to conduct the first blind survey for damped Lyα absorbers (DLAs) at low redshift (z < 1.6). Our statistical sample includes 463 quasars with spectral coverage spanning a total redshift path Δz = 123.3 or an absorption path ΔX = 229.7. Within this survey path, we identify 4 DLAs defined as absorbers with H I column density $N_{\text{H}^1} \geq 10^{20.3}$ cm$^{-2}$, which implies an incidence per absorption length $\ell_{\text{DLA}}(X) = 0.017\pm0.008$ at a median survey path redshift of $z = 0.623$. While our estimate of $\ell_{\text{DLA}}(X)$ is lower than earlier estimates at $z \approx 0$ from H I 21 cm emission studies, the results are consistent within the measurement uncertainties. Our data set is too small to properly sample the $N_{\text{H}^1}$, frequency distribution function $f(N_{\text{H}^1}, X)$, but the observed distribution agrees with previous estimates at $z > 2$. Adopting the $z > 2$ shape of $f(N_{\text{H}^1}, X)$, we infer an H I mass density at $z \sim 0.6$ of $\rho_{\text{H}^1}^{\text{DLA}} = 0.25^{+0.12}_{-0.11} \times 10^0 M_\odot$ Mpc$^{-3}$. This is significantly lower than previous estimates from targeted DLA surveys with the HST, but consistent with results from low-z H I 21 cm observations, and suggests that the neutral gas density of the universe has been decreasing over the past 10 Gyr.

Key words: evolution – galaxies: evolution – galaxies: ISM – intergalactic medium – quasars: absorption lines

Supporting material: figure set, machine-readable table

1. Introduction

Galaxy formation and evolution are critically dependent on the gas within and surrounding a galaxy. As galaxies evolve, gas is accreted onto the galaxy and expelled through various processes such as activity of an active galactic nucleus and stellar feedback. Providing observational constraints on this gas processes such as activity of an active galactic nucleus and gas is accreted onto the galaxy and expelled through various processes such as activity of an active galactic nucleus and stellar feedback.

At very low redshifts, neutral gas has been studied in detail using the HI and evolved. At very low redshifts, neutral gas has been studied in detail using the Hubble Space Telescope archive of ultraviolet (UV) quasar spectroscopy to conduct the first blind survey for damped Lyα absorbers (DLAs) at low redshift (z < 1.6). Our statistical sample includes 463 quasars with spectral coverage spanning a total redshift path Δz = 123.3 or an absorption path ΔX = 229.7. Within this survey path, we identify 4 DLAs defined as absorbers with H I column density $N_{\text{H}^1} \geq 10^{20.3}$ cm$^{-2}$, which implies an incidence per absorption length $\ell_{\text{DLA}}(X) = 0.017\pm0.008$ at a median survey path redshift of $z = 0.623$. While our estimate of $\ell_{\text{DLA}}(X)$ is lower than earlier estimates at $z \approx 0$ from H I 21 cm emission studies, the results are consistent within the measurement uncertainties. Our data set is too small to properly sample the $N_{\text{H}^1}$, frequency distribution function $f(N_{\text{H}^1}, X)$, but the observed distribution agrees with previous estimates at $z > 2$. Adopting the $z > 2$ shape of $f(N_{\text{H}^1}, X)$, we infer an H I mass density at $z \sim 0.6$ of $\rho_{\text{H}^1}^{\text{DLA}} = 0.25^{+0.12}_{-0.11} \times 10^0 M_\odot$ Mpc$^{-3}$. This is significantly lower than previous estimates from targeted DLA surveys with the HST, but consistent with results from low-z H I 21 cm observations, and suggests that the neutral gas density of the universe has been decreasing over the past 10 Gyr.

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At high redshifts, $z \gtrsim 2$, $f(N_{\text{H}^1}, X)$ for DLAs has been measured by many authors (e.g., Prochaska & Wolfe 2009; Noterdaeme et al. 2012; but see Crighton et al. 2015 and Sánchez-Ramírez et al. 2015), using large optical surveys such as the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009). These studies find that the shape of $f(N_{\text{H}^1}, X)$ is invariant between $z \sim 2$ and $z \sim 3.5$, while the normalization is observed to evolve, decreasing by a factor of $\approx 1.3$–2. This implies a concomitant decrease in $\ell_{\text{DLA}}(X)$ and $\rho_{\text{H}^1}^{\text{DLA}}$. Such evolution may be explained by either gas conversion into stars over this redshift range or feedback processes that expel gas from galaxies (e.g., Prochaska & Wolfe 2009).

A key feature of $f(N_{\text{H}^1}, X)$ and its moments is that they appear to converge by $z \sim 2$ to the present-day values estimated using H I 21 cm studies (Zwaan et al. 2005; Braun 2012; Delhaize et al. 2013; Hoppmann et al. 2015). This suggests that these quantities have remained essentially unchanged over the last 10 billion years of galaxy evolution. Unfortunately, at $z \lesssim 2$, it is difficult to measure $f(N_{\text{H}^1}, X)$ directly, because the effectiveness of optical surveys plummets due to the atmospheric absorption of ultraviolet (UV) radiation (Lanzetta et al. 1995). This problem can be circumvented by observing from space with the UV spectrographs on the Hubble Space Telescope (HST). However, due to the expense of these observations and the scarcity of DLAs in random lines of sight, large-scale blind surveys comparable to the SDSS have not been feasible within the limited time allocations of single observing programs.
To increase the rate of detection of high H\textsc{i} column density absorbers along quasar sightlines, previous studies at $z < 2$ have used several types of pre-selection methods, with the most common approach being the use of strong Mg\textsc{ii} absorption to pre-select DLA and H\textsc{i} 21 cm candidates (e.g., Briggs & Wolfe 1983; Rao & Turnshek 2000; Rao et al. 2006; Kanekar et al. 2009). At redshifts $z \gtrsim 0.1$, the Mg\textsc{ii} doublet is shifted into the optical regime. As the vast majority of DLAs show strong Mg\textsc{ii} absorption (rest equivalent width, $W_{\lambda 2796} > 0.5$ \AA), pre-selecting quasars with strong Mg\textsc{ii} absorption will significantly increase the detection rate of DLAs in the sample. However, it has not so far been straightforward to understand the biases in such pre-selections, which are critical to obtain accurate estimates of $f (N_{\text{H} I}, X)$ for DLAs (e.g., Rao et al. 2006).

Fortunately, 20 years of HST observations with a variety of UV spectrographs have resulted in a large sample of observed quasars. As HST nears the end of its mission, the time has come to explore this large data set, and perform a study in the UV to evaluate $f (N_{\text{H} I}, X)$, $f_{\text{DLA}} (X)$ and $f_{\text{H} I \text{A}}$ at $z < 1.6$, similar to earlier studies performed in the optical regime. In this paper, we use the HST spectroscopic archive to obtain a measurement of the above quantities between $z \sim 0.01$ and $z \sim 1.6$, covering the past 10 billion years of the universe. The sample for this study is described in Section 2, and the method is described in Section 3. Our results are presented in Section 4 and discussed in Section 5. Throughout this paper we adopt an ($\Omega_m$, $\Omega_{\Lambda}$, $h$) = (0.3, 0.7, 0.7) cosmology.

2. SAMPLE SELECTION

To measure the amount of neutral hydrogen between $z \sim 0.01$ and $z \sim 1.6$, we have assembled a large sample of quasars observed with medium resolution spectrographs on the HST. Specifically, we performed a search of the HST archive for quasars observed with either the Space Telescope Imaging Spectrograph (STIS), the Faint Object Spectrograph (FOS) or the Cosmic Origins Spectrograph (COS). These instruments have gratings that provide enough spectral resolution for a high fidelity search for strong absorption line systems (see Table 2 and Section 3.1). We did not include the Goddard High Resolution Spectrograph (GHRS), as its spectral coverage is too small to provide a meaningful search path. In total, a sample of 878 quasars were observed with at least one of these instruments and gratings.

We will not outline the procedure here used to analyze the spectra. Instead, we refer the reader to the following papers that describe the reduction process in detail for each of the different instruments and gratings. The FOS G160L and STIS spectra reductions are described in Ribaudo et al. (2011). We note that the FOS G160L data were cut off at a wavelength of 1350 \AA. This arbitrary cut-off does not affect the results in this paper (see Section 4). The reduction of the higher resolution FOS spectra is detailed in Bechtold et al. (2002). Finally, the analysis of the COS spectra is described in Thom et al. (2011) and Meiring et al. (2011).

The reduced spectra were compiled into a single list, and, for quasars with multiple observations with different instruments, the spectra were combined into a single spectrum. In cases of overlapping spectral coverage, the higher resolution spectrum was used. We visually confirmed the emission redshift, and the quality of the spectra for all the quasars. Several quasars are not included either due to too low signal-to-noise ratio (S/N) or bad spectra (99 quasars). We also exclude any quasars that exhibit strong broad absorption line (BAL) features (12 quasars). A total of 767 quasars satisfy the above criteria and form the sample of this paper, as tabulated in Table 1.

2.1. Statistical Sample

To provide an accurate measurement of the H\textsc{i} column density distribution function, it is critical to provide an unbiased quasar sample, as the inclusion of quasar sightlines targeted to study known absorption systems would bias $f (N_{\text{H} I}, X)$ to higher values relative to the cosmic mean. Similarly, the inclusion of quasar sightlines that were targeted to contain a known absence of absorption systems would bias $f (N_{\text{H} I}, X)$ low. We have therefore carefully considered the stated selection criteria for each of the observed quasars. In Table 1, we have included a flag that indicates if the target quasar was observed for a bias with respect to the presence of an absorber along the sightline.

The statistical flag ($f_{\text{stat}}$) can take on three values. A flag of 0 indicates the observed quasar was targeted because it contained either an absorber (i.e., a known DLA or an Mg\textsc{ii} system) or a lack of these systems along the line of sight. A flag of 1 indicates that the quasar was targeted independent of any known features along the line of sight. Finally a flag of 2 indicates that the quasar sightline crosses close to a previously recorded galaxy seen in emission. The true statistical sample defined in this paper contains only the targets with a statistical flag equal to 1, consisting of a total of 463 quasars. We also

| QSO     | $z_{\text{em}}$ | Instrument | Grating | Search Path | Statistical Path | Proposal ID |
|---------|-----------------|------------|---------|-------------|-----------------|-------------|
| J0000−1245 | 0.200           | COS        | G130M-G160M | F_search \text{b} | Min $z$ | Max $z$ | F_stat \text{c} | Min $z$ | Max $z$ | 12604 |
| J0001+0709 | 3.234           | STIS       | G230L   | 1 | 0.010 | 0.299 | 1 | 0.010 | 0.188 | 8569 |
| J0004−4157 | 2.760           | FOS        | G270H   | 1 | 1.501 | 1.695 | 0 | ... | ... | 6577 |
| J0005−0524 | 1.900           | FOS        | G270H-G190H | 1 | 0.829 | 1.695 | 1 | 0.829 | 1.695 | 4581, 6705 |
| J0005−5006 | 0.033           | COS        | G130M-G160M | 1 | 0.010 | 0.133 | 1 | 0.010 | 0.03 | 12936 |

Notes. (Omitted from this portion of the table for brevity are the columns for alternate QSO name, right ascension and declination.)

\text{a} Emission redshift of quasar.
\text{b} Search flag: (0) Low S/N or bad spectrum; (1) Included; (2) BAL quasar.
\text{c} Statistical flag: (0) Non-statistical; (1) Statistical; (2) Galaxy Sample.

(This table is available in its entirety in machine-readable form.)
define an expanded sample in this paper which contains quasars with both \( f_{\text{stat}} = 1 \) and \( f_{\text{stat}} = 2 \) (677 quasars).

### 3. METHOD

To search for absorption systems in the HST spectra, we apply a method similar to that described in Prochaska et al. (2005), but slightly adapted for our lower redshift sample. Specifically, we define the search path for each quasar sightline, with the lower limit of the search path set by the S/N of the spectrum. We determine the S/N by calculating a running median with a 20 pixel width for each wavelength. The lower limit to the search path is set to the wavelength for which this median S/N is greater than the minimum allowed S/N, which we take to be 4, or the wavelength of Ly\( \alpha \) at \( z = 0 \) (\( \lambda_{\text{Ly} \alpha} = 1215.6701 \) Å), whichever is greater. The choice of 4 for this minimum S/N is explained in Section 3.2. The upper limit to the search path is set to be either the end of the spectrum or the value \((1 + z_{\text{em}} + \text{offset})\lambda_{\text{Ly} \alpha}\), whichever is smaller. Here, \( z_{\text{em}} \) is the quasar redshift; the redshift offset is added to allow absorption systems to have slightly higher redshifts than that of the quasar. This offset redshift (chosen to be 0.1) also encompasses the uncertainty in the reported quasar emission redshifts. The complete search path is shown in the left panel of Figure 1.

For those quasars that are part of the statistical sample, we also define a statistical search path, \( g(z) \). The lower limit of the statistical path is set again by the wavelength where the median S/N exceeds the minimum S/N value of 4, or a wavelength of \((1 + \text{offset})\lambda_{\text{Ly} \alpha}\), whichever is greater. This time, we adopt a redshift offset of 0.01 which is \( \sim 3000 \) km s\(^{-1}\) from our Galaxy. This offset is introduced to prevent any biasing due to clustering in the Milky Way neighborhood. The upper limit is set to the end of the spectrum or the value \( \sqrt{(c - \Delta v)/(c + \Delta v)(1 + z_{\text{em}})\lambda_{\text{Ly} \alpha}} \), whichever is greater. Here, \( \Delta v \) is taken to be \( 3000 \) km s\(^{-1}\) which prevents clustering around the quasar from affecting our measurements. The search path for the statistical sample \( (f_{\text{stat}} = 1) \) is shown in the right panel of Figure 1.

After defining the search path, we run our search algorithm to find candidate absorption systems along the search path to each quasar. The algorithm searches regions of the spectrum that fall below a specified S/N cut, which occurs in the absorption trough of strong absorbers. Specifically, the algorithm assigns to each pixel a DLA score, which is a measure of how many pixels in a 3 Å window centered around this pixel fall below the assigned S/N cut per pixel. We take a 3 Å window because this is the core width of a \( N_{\text{HI}} = 10^{20.3} \) cm\(^{-2}\) absorber at \( z = 0.01 \), while the S/N threshold is taken to be 2. The central pixels for which greater than 60% of the surrounding pixels in the 3 Å window fall below the S/N threshold are flagged by the algorithm as candidate absorption systems. Altogether, we recorded 139 such candidates from the complete sample.

The final step in the search for absorption systems is the visual follow-up of these candidates. We fit individual absorption systems using a custom IDL Voigt-profile fitting program for DLAs, \texttt{x\_fitdl}, which is part of the the publicly available IDL library, XIDL.\(^7\) With this program, we are able to simultaneously fit both the Voigt profile and the continuum of the quasar as described in detail in Prochaska et al. (2003b). The largest source of uncertainty stems from the continuum placement.

As this process has inherently a human aspect to it, two of the authors (MN and JXP) independently carried out the fits to the candidate absorbers. The results were compared and, for most of the systems (\( \sim 90\% \)), the measured \( \text{H} \text{I} \) column density from both authors fell within the estimated 1\( \sigma \) uncertainty of the measurement. We therefore believe that our column density measurements are robust.

#### 3.1. Resolution Considerations

Low resolution spectra could result in inaccurate \( \text{H} \text{I} \) column density measurements and/or non-detection of DLAs by the search algorithm. Our lowest resolution spectra are taken with the low resolution gratings of the STIS G230L and FOS G160L, which have resolutions as low as \( R \approx 250 \). For such resolutions, only about half of a resolution element falls within the DL trough of a low column density system, and therefore small deviations could result in a non-detection of such a DLA by the search algorithm.

To assess the impact of resolution on the recovery process, we created simulated spectra with similar S/N and resolution to the observational data. We added artificial DLAs to the spectra with a range of column densities. For this mock data set, the algorithm was successful in recovering greater than 99\% of all of the absorbers with a column density above \( 10^{20} \) cm\(^{-2}\). We conclude that the resolution of the spectra is sufficient to accurately recover DLAs.

We also test our ability to recover correct \( \text{H} \text{I} \) column density measurements by adding DLAs to our lowest resolution spectra and fitting these DLAs with the fitting procedure described in Section 3. In particular, we added 50 DLAs with varying \( \text{H} \text{I} \) column densities to our lowest resolution spectra (i.e., both STIS and FOS-L) and measured their \( \text{H} \text{I} \) column densities via our fitting method. The results are shown in Figure 2. As can be seen from the figure, we are able to accurately recover the actual \( \text{H} \text{I} \) column density over the full range of input values, including the lowest column density systems. Furthermore, the lower resolution does not cause any systematic under- or over-estimate of the \( \text{H} \text{I} \) column density. The deviation around the actual value for this sample is 0.10 dex, which is comparable to the fit uncertainties (which have a mean of 0.15 dex) that we have assigned to the sample.

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\(^7\) http://www.ucolick.org/~xavier/IDL/
As a final test, we have reanalyzed the results in this paper with the lowest resolution spectra omitted from the sample, and find no significant difference in any of the result presented.

3.2. S/N Considerations

Similar to the resolution of a spectrum, the S/N of a spectrum could affect both the search algorithm’s efficacy and ability to accurately measure the H\textsc{i} column density of the absorption system during the fitting process. In the case of the search algorithm, low S/N spectra will flag more false positives as more pixels will satisfy the S/N cut criteria. To prevent high rates of false positive detections, we therefore set the minimum S/N ratio to be 4 over a 20 Å window, which is 2σ above the S/N cut of 2 per 3 Å utilized in the search algorithm.

We note that Noterdaeme et al. (2009b) found that DLAs could go undetected in the search algorithm, if they occur sufficiently blueward in the spectrum as their damping wings would keep the S/N below the S/N cut. We have visually checked all of the spectra and find no evidence that this effect is present in our sample, likely because of the decrease in Ly\textalpha forest density of these low redshift quasar sightlines.

We also need to be able to accurately determine the H\textsc{i} column density of the absorption systems with these S/N cuts. To test this, we insert artificial absorption systems in the real spectra and increase the noise level to the required S/N values. The fitting results are displayed in Figure 2. As is clear from the figure, we are able to accurately determine the H\textsc{i} column density of systems down to S/N ≈ 4 for even the lowest resolution data in the sample. The dispersion of the measured values around the actual H\textsc{i} column density for a spectrum with S/N = 4 is 0.15 dex.

We therefore conclude that a S/N threshold of 4 provides the ideal balance between maximizing the search path length while still providing the ability to reliably determine the H\textsc{i} column density of all DLAs in the search path.

4. RESULTS

4.1. The Full Sample of DLAs

Figure 3 shows the H\textsc{i} absorption profiles for all the absorbers with a measured H\textsc{i} column density greater than 10^{20.3} cm\(^{-2}\). These absorbers are also listed in Table 3. Our sample contains a total of 47 DLAs with a mean redshift of z = 0.796. Of these 47 systems, 33 were selected due to the presence of strong Mg\textsc{ii} absorption, 6 due the presence of a galaxy close to the quasar sightline, 2 were known H\textsc{i} 21 cm absorbers, and 2 were known DLAs. Only 4 DLAs were discovered in sightlines not a priori selected to contain a strong absorber, and hence form the statistical sample of this paper.

We can test our methodology and recovery rate of DLAs by comparing our list of DLAs to those found in Rao et al. (2006), as the latter is a subset of this larger sample. We find that our search algorithm recovers 28 of the 41 DLAs in the Rao et al. (2006) sample, with a mean dispersion of 0.10 dex between the H\textsc{i} column density estimates. Four of the DLAs were not
covered by our spectra either due to the cut-off at 1350 \textAA in the FOS G160L or some other reduction issue. One of these is the serendipitously discovered DLA at z = 0.0912 toward B0738 +313. However, we note that the omission of these DLAs do not affect the results in this paper, as these sightlines would not have been part of the statistical sample because of their pre-selection of Mg II absorption.

Of the remaining 9 DLAs not recovered by our search algorithm, 8 fell in a portion of the spectrum with an S/N below our criterion (see Section 3.2). We note that these sightlines are also not included in our statistical search path and therefore do not affect the conclusions presented in this paper. The only DLA (in QSO J0153+0052 at z_{abs} = 1.0599) which did fall in the search algorithm’s search path and was not detected was not found because the trough of this potential DLA showed significant flux. This could be either due to Ly\alpha emission at the redshift of the DLA, or an issue with the zero point flux of the spectrum. We have visually checked all of the spectra and believe that this is a very rare occurrence.

4.2. The Column Density Distribution Function, f(N_{HI}, X)

We obtain the H I column density distribution function with the approach described in, e.g., Tytler (1987). \( f(N_{HI}, X) \) \( dN_{HI} \) \( dX \) is defined as the number of DLAs with H I column density between \( N_{HI} \) and \( N_{HI} + dN_{HI} \) and within the absorption distance \( dX \). \( dX \) is defined as

\[
dX = \frac{H_0}{H(z)} (1 + z)^2 dz,
\]

where \( H_0 \) is the Hubble constant and \( H(z) \) is given by

\[
H(z) = H_0 (1 + z)^2 (1 + z\Omega_m) - z(z + 2)\Omega_k)^{-1/2}.
\]

The absorption distance is defined in this manner such that \( f(N_{HI}, X) \) is constant for a non-evolving population of absorbers.

The statistical sample only contains 4 DLAs, and therefore we have poor constraints on the functional form of \( f(N_{HI}, X) \). To increase the sample size, we include all sightlines selected to probe an intervening galaxy (i.e., those with \( f_{\text{stat}} = 2 \) in Table 1), resulting in a DLA sample of 9 DLAs. We note that the inclusion of these sight lines will likely bias the normalization of \( f(N_{HI}, X) \) high. The resulting \( f(N_{HI}, X) \) is shown in the left panel of Figure 4. Our results are consistent with the results of the local H I 21 cm study of Zwaan et al. (2005), and with those of DLA surveys at higher redshifts (e.g., Prochaska & Wolfe 2009; Noterdaeme et al. 2012). However, our sample size remains too small to constrain \( f(N_{HI}, X) \) at the highest H I column densities.

We also consider \( f(N_{HI}, X) \) for the sample described in Rao et al. (2006). They note that their sample contains a large number of high H I column density systems, although this deviation is not statistically significant. We have broken up our sample into those DLAs that were found using the Mg II selection criteria defined in Rao et al. (2006) and the remaining DLAs. The cumulative distribution plotted in the right panel of Figure 4 indeed shows that the Mg II-selected DLA sample has a larger number of high H I column density systems than the rest of the low-z DLA sample (this work) or the high-z DLA sample of Noterdaeme et al. (2012). This corroborates the suggestion of Prochaska & Wolfe (2009) that selecting sightlines based on metal line absorption could bias the H I distribution toward high column densities. This result is also seen in recent work on metal-strong absorbers (Dessauges-Zavadsky et al. 2009; Kaplan et al. 2010; Berg et al. 2015).

4.3. Line Density of DLAs, \( \ell_{\text{DLA}}(X) \)

The line density of DLAs, \( \ell_{\text{DLA}}(X) \), is defined as the zeroth moment of \( f(N_{HI}, X) \), i.e.:

\[
\ell_{\text{DLA}}(X) = \int_{N_{\text{DLA}}}^{\infty} f(N_{HI}, X) dN_{HI} dX,
\]

where \( N_{DLA} \) is the threshold H I column density for DLAs. In practice, \( \ell_{\text{DLA}}(X) \) is estimated by measuring the number of DLAs in a given redshift bin and then dividing this value by the total absorption path length in this redshift bin. A correlated quantity is the redshift number density, \( n_{\text{DLA}} \), which is obtained by dividing the number of DLAs found in a redshift bin by the redshift path length. Both of these quantities describe the incidence rate of DLAs along a line of sight.

We have calculated \( \ell_{\text{DLA}}(X) \) and \( n_{\text{DLA}} \) for the complete statistical sample (those with \( f_{\text{stat}} = 1 \)), which covers the redshift range, \( z = 0.01 - 1.6 \), with a median redshift of 0.623. The resultant \( \ell_{\text{DLA}}(X) \) is 0.0170.008, which equates to \( n_{\text{DLA}} = 0.0330.0295.015 \). These values are put in context by plotting them with a compilation from the literature in Figure 5.

Figure 5 shows that the line density obtained from this sample is lower than the locally measured values of Zwaan et al. (2005) and Braun (2012) (note that the latter estimate is based on an extrapolation from just three galaxies), although our estimate is consistent with these values within 2\( \sigma \) significance. Our \( \ell_{\text{DLA}}(X) \) estimate is also lower than the estimate of Rao et al. (2006), but the systematic uncertainties in their measurement are difficult to quantify.

Our new estimate of the line density of DLAs at \( z < 1.6 \) is lower than this value at \( z \sim 2 \) (Noterdaeme et al. 2012) at greater than 2\( \sigma \) significance. This result suggests that \( \ell_{\text{DLA}}(X) \)
has evolved over this redshift range. This result is discussed further in Section 5.

We note that we have searched for evolution within our sample by dividing the sample into two subsamples at the median redshift of $z = 0.623$. However, the sample size is too small to discern any evolution within the sample, although the sample is consistent with an evolution of $<0.05$ in $t_{\text{DLA}}(X)$ per unit redshift, which agrees with the evolution at higher redshift ($\sim0.03$ in $t_{\text{DLA}}(X)$ per unit redshift, see, e.g., Sánchez-Ramírez et al. 2015).

4.4. Mass Density of $\text{H}_1$, $\rho_{\text{H}_1}^{\text{DLA}}$

The final quantity we consider is the first moment of $f(N_{\text{H}_1}, X)$, which is the mass density of $\text{H}_1$ contained in
DLAs, $\rho_{H_1}^{\text{DLA}}$. This quantity is defined by

$$\rho_{H_1}^{\text{DLA}} = \frac{m_{H}H_{0}}{c} \int_{N_{\text{min}}}^{N_{\text{max}}} N_{H_1} f(N_{H_1}, X) dN dX,$$

where $m_{H}$ is the mass of the hydrogen atom and $c$ is the speed of light. The superscript clarifies that we are only measuring the fraction of $H_1$ in DLAs; of course, as noted earlier, these systems contain the bulk (>85%) of the $H_1$ at all redshifts (Zwaan et al. 2005; O’Meara et al. 2007; Noterdaeme et al. 2012). We also note that literature studies often provide estimates of the cosmological neutral gas mass density, $\Omega_{g}^{\text{DLA}}$. $\rho_{H_1}^{\text{DLA}}$ is related to $\Omega_{g}^{\text{DLA}}$ by the conversion factor $\mu/\rho_{c}$, where $\mu$ is the mean molecular mass of the gas and $\rho_{c}$ is the critical density of the universe.

As with $f(N_{H_1}, X)$, $\rho_{H_1}^{\text{DLA}}$ cannot be accurately determined from our own study because the small sample size lacks the statistics to accurately determine the number of high $H_1$ column density ($N_{H_1} \gtrsim 10^{21} \text{ cm}^{-2}$) systems (none are present in our survey). These systems are likely to contribute significantly to $\rho_{H_1}^{\text{DLA}}$ (Zwaan et al. 2005; O’Meara et al. 2007; Noterdaeme et al. 2012), and our results are hence likely to underestimate the underlying neutral gas density. To account for this, we assume that the mean column density of the low redshift absorber sample is unchanged from the mean column density at high redshifts, as measured by Noterdaeme et al. (2012; see Section 4.2).

Our data yield $\rho_{H_1}^{\text{DLA}} = (0.10^{+0.08}_{-0.05} \times 10^{5} M_{\odot} \text{ Mpc}^{-3})$ over the redshift range $0.01 \lesssim z \lesssim 1.6$, without any correction for the missing high $H_1$ column density absorbers. Using the mean $H_1$
column density estimate of Noterdaeme et al. (2012) to account for their absence, we obtain a corrected $\rho_{H_1}^{DLA}$ of $0.25^{+0.20}_{-0.12} \times 10^3 M_\odot \text{Mpc}^{-3}$. Both the corrected (solid error bars) and uncorrected (dashed error bars) values are shown in Figure 6, along with other estimates of this quantity at different redshifts from the literature.

Our corrected estimate of $\rho_{H_1}^{DLA}$ is lower than the earlier estimate over the same redshift range by Rao et al. (2006). The lower value compared to that of Rao et al. (2006) is due to both the decrease in $\ell_{DLA}(X)$ and the lower adopted mean H I column density (see Section 4.2). Our H I mass density estimate is, however, in good agreement with the estimates from H I 21 cm studies at $z \approx 0-0.3$ (Zwaan et al. 2005; Lah et al. 2007; Delhaize et al. 2013; Rhee et al. 2013; Hopmann et al. 2015). The results suggest a mild evolution in $\rho_{H_1}^{DLA}$, driven by the evolution in $\ell_{DLA}(X)$, which was recently quantified by Crighton et al. (2015) and Sánchez-Ramírez et al. (2015) who measured $\rho_{H_1}^{DLA}$ at high redshifts.

Finally, we would like to point out the apparent discrepancy in the $\rho_{H_1}^{DLA}$ measurements of Prochaska & Wolfe (2009) and Noterdaeme et al. (2012) at $z \approx 3$. This discrepancy is due to two factors: (i) the sample analyzed by Prochaska & Wolfe (2009) led to an under-estimate in the break in $J(N_{H_1}, X)$ by $\approx 0.2$ dex and therefore an under-estimate of $\rho_{H_1}$ by $\approx 20$%; (ii) the results are now limited by systematic uncertainties that include the approach to measuring $N_{H_1}$ dust obscuration, and color-selection bias in quasar surveys. These systematic errors must be addressed before further progress can be made in this field.

5. SUMMARY AND DISCUSSION

In this paper, we have used a large sample of quasars (767 systems) observed with the UV spectrographs on the HST to carry out a search for low-redshift DLAs. Of the 46 DLAs found in this study, only 4 are drawn from the statistical sample. The remainder were drawn from sightlines with foreknowledge of either an absorber or an intervening galaxy, or the lack of an absorber, close to or along the quasar line of sight.

Our statistical sample enables an unbiased determination of the line density of DLAs, $\ell_{DLA}(X)$, over the redshift range $0.1 \leq z \leq 1.6$. We obtain $\ell_{DLA}(X) = 0.017^{+0.014}_{-0.008}$ significantly smaller than the previous estimate of Rao et al. (2006), which appears likely to be biased high. Unfortunately, current estimates of $\ell_{DLA}(X)$ at these redshifts continue to suffer from the small sample size of quasar sightlines.

Previous studies, e.g., Prochaska et al. (2005), Rao et al. (2006), Prochaska & Wolfe (2009), and Noterdaeme et al. (2012), have claimed little evolution in the line density of DLAs in the past 10 Gyr. However, the results in this paper indicate that the line density at $z \approx 0.5$ is lower than estimates of this quantity at $z \approx 2$ at greater than $2\sigma$ significance. This suggests a mild evolution in $\ell_{DLA}(X)$ at low redshifts can be explained if the majority of galactic-scale dark matter halos are fully assembled by $z \approx 2$, and, if the neutral hydrogen content of these halos slowly decreases, either by star formation or feedback processes.

One caveat to this result is the possibility of systematic errors that can bias our estimates low. Here we discuss three of these biases. One potential bias to our sample is the exclusion of sightlines that were targeted to pass close to foreground galaxies. A random sample of quasars would contain some sightlines that pass by intervening galaxies, and by removing all of these quasars from the sample, we could bias our result low. To estimate the effect of this potential bias, we include all sightlines that are specifically chosen to cross a foreground galaxy (i.e., the quasars with $f_{int} = 2$). The resultant line density is $\ell_{DLA}(X) = 0.030^{+0.014}_{-0.010}$, which is well within the $1\sigma$ statistical uncertainty of our original estimate, indicating that this bias is smaller than our uncertainties.

A second possible bias may arise due to the inclusion of sightlines at redshifts $z > 0.3$. For these redshifts, metal lines (in particular Mg ii) would fall within the optical part of the quasar spectrum. The target selection criteria for the quasar sample may have included a lack of metal line systems in the optical part of the quasar spectrum. Similarly, by excluding all of the sightlines with known Mg ii systems, we might be biasing ourselves against quasars with metal lines in their sightlines. To test the bias in our sample against Mg ii systems, we have compared the line density of Mg ii systems in our quasar sample with the line density in the sample of Seyffert et al. (2013). We find that the line density of Mg ii systems is 0.119 over the full redshift range probed by the quasars in our statistical sample, which are also part of the sample of Seyffert et al. (2013) ($n = 93$ quasars). This value agrees well with the measured line density of $0.123 \pm 0.001$ over the slightly larger redshift range covered by the full sample of Seyffert et al. (2013), and hence we assert that this effect is unlikely to significantly bias our results.

Finally, the third possible source of bias is that against sightlines with a large amount of dust. This bias has been studied in detail using spectroscopy of radio-selected samples in high-z DLAs (e.g., Ellison et al. 2001; Akerman et al. 2005; Jorgenson et al. 2006) as well as dust reddening of quasars in SDSS (e.g., Murphy & Liske 2004; Frank et al. 2010; Fukugita & Ménard 2015; Murphy & Bernet 2016). This bias is
correlated with the amount of metals in the gas (Vladilo & Péroux 2005), and therefore is amplified at low-z due to the higher metallicity of low-z DLAs (e.g., Prochaska et al. 2003a; Rafelski et al. 2012, 2014).

Following Vladilo & Péroux (2005), dust extinction becomes significant at zinc column densities greater than ~10^{13.5} cm^{-2}, an assertion corroborated by the few DLAs showing distinct dust signatures (Noterdaeme et al. 2009a; Kulkarni et al. 2011; Ma et al. 2015). For low column density DLAs (log N_{HI} < 20.5) these zinc column densities imply [M/H] > 0.5. Such systems are expected to be rare, both from metallicity measurements of lower column density systems, and metallicity measurements from star-forming galaxies (e.g., Tremonti et al. 2004). Since \( \alpha_{DLA}(X) \) is dominated by low HI column density systems, we assert that the effect of dust on biasing this result is small. In passing, we note that the amount of dust reddening in quasars with DLAs is observed to be small at \( z \approx 2 \) (Murphy & Liske 2004), and evolves only slightly between redshifts 2.1 and 4.0 (Murphy & Bernet 2016) further suggesting that dust is not likely a large biasing factor.

We estimate the HI column density distribution function, \( f(N_{HI}, X) \), and the HI gas density, \( \rho_{HI}^{DLA} \), from our statistical sample. However, the limited sample size means that the errors on the inferred quantities are large. We find that the HI column density distribution function in our low redshift sample is consistent with the \( f(N_{HI}, X) \) measured at high redshift. The increase in the high HI column density systems found by Rao et al. (2006) could be due to their selection process, but we cannot assert this correlation with the current data set.

The HI mass density, \( \rho_{HI}^{DLA} \), is estimated to be \( 0.25 \pm 0.20 \times 10^3 M_{\odot} \text{pc}^{-3} \), after correcting for the lack of statistics at the high HI column density end due to our small sample size of DLAs. The correction makes the assumption that the mean HI column density of our low-z DLA sample is the same as that of the high-z DLA sample, as measured from the SDSS surveys (Noterdaeme et al. 2012). Our value of \( \rho_{HI}^{DLA} \) is markedly lower than that obtained in previous measurements at these redshifts, but is in agreement with estimates of the HI mass density at \( z \approx 0.3 \) using high HI 21 cm studies (Zwaan et al. 2005; Lah et al. 2007; Delhaize et al. 2013; Rhee et al. 2013; Hopmann et al. 2015). The apparent mild evolution seen in \( \rho_{HI}^{DLA} \) from \( z \approx 2 \) arises due to the evolution in \( \alpha_{DLA}(X) \), since we have assumed a non-evolving mean HI column density.

In conclusion, this study has compiled the largest sample of quasars observed in the UV with spectral resolution sufficient to search for low-redshift DLAs. Even with a total of 767 quasars in our target sample, the final sample of DLAs in these spectra is small, containing only 46 DLAs. This is in part due to the smaller than expected incidence rate of DLAs compared to the measurements from MgII surveys (Rao et al. 2006). However, the lower incidence rate is in agreement with both the results at \( z \approx 2 \) and \( z \approx 0 \), if we assume a mild decrease in \( \alpha_{DLA}(X) \) over this redshift range.

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