The SDSS-DR5 Survey for Proximate Damped Lyα Systems

Jason X. Prochaska, Joseph F. Hennawi, and Stéphane Herbert-Fort

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ABSTRACT

Using the Sloan Digital Sky Survey Data Release 5 (SDSS-DR5), we survey proximate damped Lyα systems (PDLAs): absorption-line systems with H i column density \( N_{\text{H}i} \geq 2 \times 10^{20} \text{ cm}^{-2} \) at velocity separation \( \delta v < 3000 \text{ km s}^{-1} \) from their background quasar. Many of these absorbers may be physically associated with their background quasars, and their statistics allow us to study quasar environments out to \( z \sim 5 \). However, the large ionizing flux emitted by a quasar can ionize the neutral gas in a nearby galaxy, possibly giving rise to a “proximity effect,” analogous to the similar effect observed in the Lyα forest. From a sample of 108 PDLAs, we measure the H i frequency distribution \( f(N_{\text{H}i}, X) \), incidence, and gas mass density of the PDLAs near luminous quasars over the redshift interval \( z = 2.2–5 \). The incidence and mass density of PDLAs at \( z \sim 3 \) is approximately twice that of intervening DLAs, while at \( z < 2.5 \) and \( >3.5 \) the \( f(N_{\text{H}i}, X) \) distribution is enhanced but statistically consistent with the intervening population. We interpret the observed enhancement of PDLAs around quasars in terms of quasar-galaxy clustering and compare the strength of the clustering signal to the expectation from independent measures of the respective clustering strengths of DLAs and quasars, as well as a complementary analysis of the clustering of absorbers around quasars in the transverse direction. We find that there are a factor of 5–10 fewer PDLAs around quasars than expected and interpret this result as evidence for the hypothesis that the ionizing flux from the quasars photoevaporates H i in nearby DLA galaxies, thus reducing their cross section for DLA absorption. This constitutes the first detection of a “proximity effect” for DLAs.

Subject headings: quasars: absorption lines

Online material: color figures, machine-readable table

1. INTRODUCTION

Although quasars are believed to reside at the centers of massive galaxies, which are themselves located in groups or clusters, their spectra rarely exhibit the absorption signature of either their host’s neutral interstellar medium (ISM) or the ISMs of associated nearby galaxies.\(^5\) At \( z \approx 3 \), we expect star-forming galaxies to exhibit an ISM comprised of neutral hydrogen. If the quasar sight line penetrates this ISM, it will absorb light along the hydrogen Lyman series, with strongest absorption at Lyα: \( \lambda_{\text{Ly}} = 1215.67 \text{ Å} \). Systems with H i column densities \( N_{\text{H}i} \), exceeding \( 2 \times 10^{20} \text{ cm}^{-2} \) are termed damped Lyα (DLA) systems owing to the strong damping wings that they exhibit (see Wolfe et al. 2005 for a review). Gas clouds at these high column densities, characteristic of a galactic disk, are optically thick to Lyman continuum (\( \tau_{\lambda L} \gg 1 \)) photons, giving rise to a neutral interior self-shielded from the extragalactic ionizing background.

One might guess that the absence of DLAs near most quasars is related to the large ionizing flux emitted by the quasar. In particular, for a quasar at \( z \approx 3 \) with an \( i \)-band magnitude of \( i = 19.1 \), the flux of ionizing photons is 400 times higher than that of the extragalactic UV background at a comoving distance of \( 1 h^{-1} \text{ Mpc} \) (corresponding to Hubble flow velocity of 100 km s\(^{-1}\)), and increasing as \( r^{-2} \) toward the quasar. Indeed, the decrease in the number of optically thin absorption lines (\( \log N_{\text{H}i} < 17.2 \), hence \( \tau_{\lambda L} \leq 1 \)) in the vicinity of quasars, known as the proximity effect (Bajtlik et al. 1988), is well studied and has been detected (Scott et al. 2000; Faucher-Giguere et al. 2007).

On the other hand, it has long been known that quasars are associated with enhancements in the distribution of galaxies (Bahcall et al. 1969; Yee & Green 1984, 1987; Bahcall & Chokshi 1991; Smith et al. 2000; Brown et al. 2001; Serber et al. 2006; Coil et al. 2007), although these measurements of quasar-galaxy clustering are mostly limited to low redshifts \( z \sim 1.0 \). Recently, Adelberger & Steidel (2005) measured the clustering of Lyman break galaxies (LBGs) around luminous quasars in the redshift range \( 2 \leq z \leq 3.5 \) and found a best-fit correlation length of \( r_0 = 4.7 h^{-1} \text{ Mpc} \) (\( \gamma = 1.6 \)), very similar to the autocorrelation length of \( z \sim 2–3 \) LBGs (Adelberger et al. 2003, 2005).

Cooke et al. (2006) recently measured the clustering of LBGs around DLAs and measured a best-fit \( r_0 \) of \( 2.9 h^{-1} \text{ Mpc} \) with \( \gamma = 1.6 \), with large uncertainties (see also Gawiser et al. 2001; Bouché & Lowenthal 2004). If LBGs are clustered around quasars and DLAs, might we expect DLAs to be clustered around quasars? This is especially plausible in light of recent evidence that DLAs arise from a high-redshift galaxy population that are not unlike LBGs (Möller et al. 2002).

Can DLAs continue to self-shield against the large flux of ionizing photons emitted by quasars, or are they photoevaporated? Is the distribution of DLAs around quasars dominated by ionization effects, or does galaxy clustering around the quasars dominate? Does the column density distribution of DLAs near quasars differ from the distribution in average places in the universe? What can quasar-DLA clustering teach us about quasars and the physical nature of high-redshift galaxies?

In this paper, we take positive steps toward answering these questions by measuring the abundance and distribution of DLAs.
near quasars. Recently, Prochaska et al. (2005, hereafter PHW05) surveyed the quasar spectra of the Sloan Digital Sky Survey (SDSS) Data Release 3 (Abazajian et al. 2005) for damped Ly$\alpha$ systems at $z > 2.2$. The statistical survey, comprising over 500 DLA systems, provides a relatively precise measure of the incidence of intervening DLA systems per unit redshift, $\ell(z)$, from $z = 2.2$ to 4. To focus on the cosmic average of $\ell(z)$ and avoid biases from the quasar environment, PHW05 excluded proximate DLAs (PDLAs) from their analysis, which are defined to be DLAs with velocity offset $\delta v < 3000$ km s$^{-1}$ from the emission redshift of the background quasars $^6$ (e.g., Weymann et al. 1979; Møller et al. 1998). Here we present the results of a survey for PDLA systems in the full SDSS Data Release 5 (DR5; Adelman-McCarthy et al. 2007).

$^6$ At $z = 3$, $\delta v = 3000$ km s$^{-1}$ corresponds to roughly 30 comoving Mpc h$^{-1}$ assuming $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

The first statistical study of PDLAs was performed by Ellison et al. (2002), who surveyed their sample of radio-selected QSOs at $z \sim 3$. Our work is motivated by this and several recent, closely related studies. First, Russell et al. (2006, hereafter REB06) have previously performed a search of a subset of the SDSS-DR3 quasar spectra for PDLAs over the redshift interval $2.5 < z < 4.5$. They reported an enhancement of $\ell(z)$ for DLA systems with $\delta v < 3000$ km s$^{-1}$ and, oddly, an enhancement of PDLAs with $3000$ km s$^{-1} < \delta v < 6000$ km s$^{-1}$, corresponding to very large comoving distances ($30-60$ h$^{-1}$ Mpc) from the quasar if interpreted as Hubble flow. Our search builds on their work, but we survey the larger SDSS-DR5 to recover a final sample with nearly an order of magnitude more PDLA systems. Second, Hennawi et al. (2006) published a large sample of optically thick absorption-line systems in the vicinity of $z \sim 2.5$ quasars, which were identified using a background line of sight (LOS) in close projected quasar pair systems. Based on this sample, Hennawi & Prochaska (2007) measured the cross-correlation function between foreground quasars at $z \sim 2.5$ and optically thick $N_{\text{HI}} > 10^{19}$ cm$^{-2}$ absorbers, detected in the background quasar spectra. Their measurement of the transverse clustering of absorbers around quasars should be commensurate with the incidence of similar systems along the line of sight, provided that the clustering pattern of absorbers around quasars is isotropic. However, Hennawi & Prochaska (2007) argued that the strength of the transverse clustering predicts that $\sim 15\%-50\%$ of all quasars should show a $N_{\text{HI}} > 10^{19}$ cm$^{-2}$ absorber within $\delta v < 3000$ km s$^{-1}$, which is certainly not observed. Finally, another goal of our survey is to identify candidates for follow-up observations to study Ly$\alpha$ emission from PDLAs, which could possibly yield insights into fluorescent Ly$\alpha$ recombination radiation from DLAs, the size of DLA galaxies, and the physics of Ly$\alpha$ halos surrounding high-$z$ quasars (Hennawi et al. 2008).

In the following section we describe the survey and search for PDLA candidates, and in § 3 we discuss their $N_{\text{HI}}$, measurements. A new estimate of the quasar redshifts with PDLA candidates is given in § 4. The H$\alpha$ frequency distribution and incidence of PDLA systems is presented in § 5, and we discuss these results in terms of clustering and the proximity effect in § 6. We summarize and conclude in § 7. Throughout the paper we adopt

![Figure 1](image_url)  
**Fig. 1.—Curves of the redshift selection function $g(z)$ as a function of redshift for (top) quasars satisfying the search criterion of PHW05 for DLAs drawn from the SDSS-DR3; (middle) quasars drawn from the SDSS-DR5 for a search within $v_{\text{proj}} = 6000$ km s$^{-1}$ of the quasar emission redshift $z_{\text{em}}$, and (bottom) quasars drawn from the SDSS-DR5 for a search with $v_{\text{proj}} = 3000$ km s$^{-1}$ of $z_{\text{em}}$. The bin size in the figure is $\Delta z = 10^{-3}$. [See the electronic edition of the Journal for a color version of this figure.]**

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**Table 1**

| Plate | MJD | FiberID | Name | $z_{\text{proj}}$ | $z_{\text{new}}$ | $f_{\text{H}\alpha}$ | $z_{\text{d}}$ | $z_{\text{candidate}}$ |
|-------|-----|---------|------|------------------|-----------------|-----------------|-----------|------------------|
| 750 | | | | | | | | |
| 650 | | | | | | | | |
| 750 | | | | | | | | |
| 650 | | | | | | | | |
| 750 | | | | | | | | |
| 52235 | 52143 | 52143 | 52143 | 52143 | 52143 | 52143 | 52143 | 52143 |
| 82 | 178 | 500 | 519 | 556 | 111 | 608 | 36 | 604 |
| J000009.38+135618.4 | J000500.60+102155.8 | J000143.41+152017.4 | J000159.12+094712.4 | J000221.11+002149.4 | J000238.41+101149.8 | J000300.34+160027.7 | J000303.34+105150.6 | J000413.63–085529.5 |
| 2.240 | 2.640 | 2.638 | 2.308 | 3.057 | 3.941 | 3.675 | 3.484 | 2.424 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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.

$^a$ Quasar redshift reported in SDSS-DR5.

$^b$ New quasar redshift estimated using the algorithms developed by Hennawi et al. (2006) and Shen et al. (2007). This analysis was performed on quasars with PDLA candidates lying within 10,000 km s$^{-1}$ of the SDSS-DR5 redshift.

$^c$ New intrinsic absorption; $^d$ weak intrinsic absorption ($W_{C_\alpha} < 3$ Å), included in analysis; $^e$ strong intrinsic absorption ($W_{C_\alpha} > 3$ Å), excluded.

$^f$ Starting redshift for the PDLA search assuming an offset of $v_{\text{proj}} = 3000$ km s$^{-1}$ from the quasar, allowing for the revised redshifts in col. (6).
2. SURVEY DESIGN AND PDLA CANDIDATES

We began with the full SDSS-DR5 sample of ~67,000 spectroscopically classified quasars. The SDSS fiber-fed spectrometer gives a FWHM resolution of ~2 Å and wavelength coverage spanning 3800–9200 Å. Following PHW05, we demanded that the quasar spectrum exhibit at least one region where the median signal-to-noise ratio (S/N) of 20 consecutive pixels equals or exceeds 4. This requirement eliminates many of the quasars at z > 4, which have poorer S/N data. For each QSO, we determine starting and ending redshifts $z_i$ and $z_f$, respectively, that determine the search path of that object:

$$ (\Delta z)_j \equiv (z_i - z_f)_j, $$

(1)

In the PHW05 analysis, $z_f$ corresponded to the first pixel where the data satisfied the S/N requirement under the restriction that this does not occur within 10,000 km s$^{-1}$ of the Ly$\beta$/O vi emission region of the QSO.\(^7\) For a search focusing on PDLA systems, we define $z_i$ to be a velocity $v_{\text{prox}}$ blueward of $z_{\text{em}}$ under a strict restriction: the quasars must also satisfy the S/N criterion at a velocity greater than 3000 km s$^{-1}$ + $v_{\text{prox}}$ from the QSO. We adopt this restriction for two reasons: (1) we wish to keep the presence of a DLA system with $v$ = $v_{\text{prox}}$ from biasing the S/N below our criterion; (2) as discussed in § 3, we wish to maintain a search path $(\Delta z)$, for each QSO to be set exactly by $v_{\text{prox}}$.

The total redshift search path of the survey can be summarized by its sensitivity function (e.g., Lanzetta 1993):

$$ g(z) = \sum_j \Theta(z)_j, $$

(2)

where $\Theta(z)$, is unity if $z + \delta z$ is included within a given quasar’s search path $(\Delta z)_j$, and zero otherwise. The $g(z)$ function for the SDSS-DR5 database is shown in Figure 1 for $v_{\text{prox}}$ = 3000 and 6000 km s$^{-1}$ (bottom and middle curves, respectively). For comparison, we show the same quantity for the intervening DLA search of PHW05 (corrected for the error described in footnote 7). In contrast to the intervening $g(z)$ curve, the PDLA $g(z)$ curves show significantly more structure. The $g(z)$ curves closely track the redshift distribution of SDSS quasars, and most of the structure is the result of the SDSS quasar target selection algorithm (Richards et al. 2004). On average, the intervening DLA search path is ~10 times higher than the PDLA path for $z < 3.5$ and ~5 times higher at $z \approx 4$. If the incidence of PDLA systems matches that of intervening DLAs, then we will expect to find a statistical sample with ~10 times fewer systems than PHW05, i.e., ~75 systems.

Every quasar with an emission redshift $z_{\text{em}}$ measured to be greater than 2.2 by the SDSS pipeline was searched for a PDLA candidate. This lower limit to the PDLA search results from the blue wavelength cutoff of the SDSS spectral coverage ($\lambda_{\text{min}}$ ~ 3800 Å). The search algorithm is nearly identical to the algorithm described in PHW05 for intervening absorbers, only modified to find candidates up to 7000 km s$^{-1}$ redward of $(1 + z_{\text{em}}) \times 1215.67$. The algorithm keys on any regions in the spectrum.

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\(^7\) Note that PHW05 failed to implement this restriction in their published sample. Although the differences from the computed statistics of the intervening DLA systems are small, future analyses by those authors will properly implement the algorithm, and the authors provide the correct SDSS-DR5 statistical sample at http://www.ucolick.org/~xavier/SDSSDLA. The analysis here includes the proper statistical sample.
where the S/N is coherently low over a window of $\approx 25$ Å. The algorithm triggers on the cores of damped Ly$\alpha$ systems, but also on the metal line absorption features of strong BAL systems. Therefore, we removed BAL quasars from the search sample; all of the SDSS-DR5 quasars were visually inspected, and those exhibiting very strong C iv profiles at $z \approx z_{\text{em}}$ were eliminated. Because many PDLA systems will exhibit strong C iv absorption, we chose to flag only those where the C iv doublet is blended with itself (i.e., $\Delta v_{\text{CIV}} > 500$ km s$^{-1}$) and the rest equivalent width $W_{\lambda}$ exceeds $\approx 3$ Å. We admit, however, that this “by-eye” analysis is somewhat subjective, and, in general, we conservatively included borderline cases under the expectation that a true BAL would not show damped Ly$\alpha$ absorption because the quasar radiation field will have photoionized the hydrogen gas. All of the quasars comprising the search are listed in Table 1.

### 3. $N_{\text{H}}$, MEASUREMENTS

Our procedure to measure the $N_{\text{H}}$, values of the PDLA candidates follows that of PHW05, and, in fact, we adopt their published values for PDLA candidates from Data Release 3. For each new PDLA candidate, we searched for the presence of metal line absorption near the redshift of the Ly$\alpha$ centroid. Because the absorption redshift coincides with the quasar emission redshift ($z_{\text{abs}} \approx z_{\text{em}}$), the strong low-ion transitions of Si ii $\lambda 1206$, C ii $\lambda 1334$, and Al ii $\lambda 1670$ generally lay clear of the Ly$\alpha$ forest, and we found that nearly every PDLA system exhibited at least one of these transitions. We defined $z_{\text{abs}}$ to be the centroid of the strongest, unblended low-ion transition. In the few cases without apparent metal line absorption, we determine $z_{\text{abs}}$ by centroiding the damping wings of the Ly$\alpha$ profile.

We then fit a Voigt profile to the candidate’s Ly$\alpha$ profile while also estimating the quasar continuum. The latter effort is significantly complicated by the quasar’s Ly$\alpha$ and N v emission lines. We guided the continuum placement by the observed heights of the Ly$\beta$ and C iv emission features, but the systematic uncertainty related to this exercise dominates the errors reflected in our measurements of $N_{\text{H}}$. Therefore, while we have reported relatively conservative errors for the measurements, we are certain that...
the error distribution is non-Gaussian. For example, the probability of an error greater than 3 \( \sigma \) is not necessarily less than 0.27\%. Tests with mock SDSS spectra (PHW05) do give us confidence that 95\% of the values lie within 2 \( \sigma \) of the reported \( N_{\text{H}} \) measurements. All of the systems with measured \( N_{\text{H}} \) \( \geq 2 \times 10^{20} \) cm\(^{-2}\) are listed in Tables 2 and 3. The former lists the PDLAs in the statistical sample, whereas the latter table presents PDLAs identified in BAL quasars or low S/N spectra.

A set of representative fits is shown in Figure 2. One notes, in several cases, that the challenges of continuum placement (dotted line) near the Ly\( \alpha \) emission line. One also notes cases where the PDLA Ly\( \alpha \) profile is significantly redward of the quasar’s Ly\( \alpha \) emission line. This is a clear indication that determinations of \( z_{\text{em}} \) based primarily on Ly\( \alpha \) emission will give a poor result. We return to this issue in the following section. Finally, we wish to briefly compare the \( N_{\text{H}} \) values that we derived with those reported in REB06 (measured from the same spectra). As REB06 noted, the agreement between their values and PHW05 is good. We identify a few cases (e.g., the DLA at \( z = 3.958 \) toward J111224.18+004630.3), however, where we find much lower \( N_{\text{H}} \) values than REB06. In these cases, we have verified our lower values by analyzing the corresponding Ly\( \beta \) profile.

4. NEW MEASUREMENTS OF QUASAR REDSHIFTS

In Figure 3a we present a histogram of the velocity offsets, \( \delta v = c ( R^2 - 1 ) / R^2 + 1 \), with \( R \equiv (1 + z_{\text{abs}})/(1 + z_{\text{em}}) \) between \( z_{\text{abs}} \) for all of the fitted PDLA candidates and \( N_{\text{H}} \) from its corresponding quasar as listed in the SDSS-DR5 database. It is evident from the figure that the quasar redshifts are systematically in error. The presence of very few PDLA candidates with \( \delta v \approx 0 \) km s\(^{-1}\) and, more importantly, many examples with \( \delta v < -1000 \) km s\(^{-1}\) suggests that the Ly\( \alpha \) absorption profiles of PDLA systems have significantly biased the measurement of \( z_{\text{em}} \) away from its correct value. It is well known that the primary rest-frame ultraviolet quasar emission lines, which are redshifted into the optical for \( z > 2 \), can differ by up to \( \sim 3000 \) km s\(^{-1}\) from systemic, due to outflowing/inflowing material in the broad-line regions of quasars (Gaskell 1982; Tytler & Fan 1992; Vanden Berk et al. 2001; Richards et al. 2002). The quasar redshifts provided by the SDSS spectroscopic pipeline come from a maximum likelihood fit to multiple emission lines (see, e.g., Stoughton et al. 2002), which does not result in robust systemic redshifts estimates. Concerned that the errors in \( z_{\text{em}} \) will significantly affect our clustering analysis, we estimated the systemic emission redshift of every QSO with a PDLA candidate exhibiting \( N_{\text{H}} \) \( > 10^{20} \) cm\(^{-2}\) and \( \delta v < 10,000 \) km s\(^{-1}\), following the approach described in Shen et al. (2007; see also Hennawi et al. 2006). Shen et al. (2007) measured the correlation between the relative shifts of the high-ionization emission lines Si \( iv \), C \( iv \), and C \( iii \), and the shift between these respective lines and the Mg \( ii \) line. Because the redshift defined by Mg \( ii \) is tightly correlated with the systemic redshift (Richards et al. 2002), the Shen et al. (2007) approach exploits these correlations to “shift” into the systemic frame. The emission lines in the SDSS spectra were centered using the algorithm described in Hennawi et al. (2006), which was also employed by Shen et al. (2007). The updated redshifts are presented in column (6) of Table 1.

\[ \delta v = c ( R^2 - 1 ) / R^2 + 1 \]

\[ R \equiv (1 + z_{\text{abs}})/(1 + z_{\text{em}}) \]

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8 The complete set of fits can be found at http://www.ucolick.org/~xavier/SDSSDLA.
1969) defined to give a constant line density of absorbers if their velocities are near 10,000 km s$^{-1}$. This analysis demonstrates that there are significant systematic errors in the emission redshifts; note, especially, that there are few examples with $z_{\text{em}} > 1000$ km s$^{-1}$ and $\delta v < 0$ km s$^{-1}$. These results motivated us to remeasure the redshifts of all quasars with a PDLA candidate within 10,000 km s$^{-1}$ of the Journal for a color version of this figure.

In Figure 3b, we present the velocity offsets for all PDLA candidates with $\delta v < 10$, 000 km s$^{-1}$. We note a nearly smooth distribution of systems with $\delta v > 0$ km s$^{-1}$ and 33 PDLAs with $\delta v < 0$ km s$^{-1}$ out of 108 PDLA systems with $\delta v < 3000$ km s$^{-1}$. Although we expect that the revised redshifts still suffer from systematic uncertainties, we are optimistic that the uncertainty is smaller than a few hundred kilometers per second and, more importantly, that the errors are symmetrically distributed. One may be concerned that we have restricted the new $z_{\text{em}}$ measurements to a subset of the SDSS-DR5 QSO database. As discussed below, because we include all PDLA systems with negative $\delta v$ in our clustering analysis, the errors in $z_{\text{em}}$ for quasars without PDLA candidates should have minimal effect on our results.

5. THE $\text{H I}$ FREQUENCY DISTRIBUTION AND ITS MOMENTS

5.1. $f(N_{\text{HI}}, X)$

Akin to the luminosity function of galaxies, the fundamental measure of a DLA sample is its $\text{H I}$ frequency distribution, $f(N_{\text{HI}}, X)$. Here $X$ is the absorption distance (Bahcall & Peebles 1969) defined to give a constant line density of absorbers if their number density and cross section remain fixed in time. Following PHW05, we have calculated $f(N_{\text{HI}}, X)$ for the PDLA systems.

5.2. Log-N distribution

In Figure 4, we show the frequency distribution $f(N_{\text{HI}}, X)$ of the PDLA systems at $z > 2.2$ drawn from SDSS-DR5 (binned data points). Overplotted on the data are three curves corresponding to the solutions from maximum likelihood analyses: (1) a single power-law fit to the PDLA data, (2) a $\Gamma$-function fit to the PDLA data, and (3) the $\Gamma$-function fit (with 1 $\sigma$ uncertainty indicated by the gray band) to the SDSS-DR3 sample of intervening DLA systems (PHW05) renormalized to match the incidence of PDLA systems at $z > 2.2$. The maximum likelihood solutions are overplotted in the figure. The power law has exponent $\alpha_1 = -2.1 \pm 0.1$, while the $\Gamma$-function has a similar power-law slope and allows any value of $N_{\text{HI}} > 6$ at the 98% confidence level. We conclude that the PDLA sample does not show a break from a single power-law model. For comparison, we also show the best-fit $\Gamma$-function for $f(N_{\text{HI}}, X)$ of intervening DLAs from PHW05 renormalized to give the same number of PDLA systems as observed. The shaded region shows the approximate 1 $\sigma$ uncertainty in the shape of this $\Gamma$-function.

The figure suggests that the $N_{\text{HI}}$ values of the PDLA sample are not drawn from the same parent population as intervening DLA systems. We find, however, that a two-sided Kolmogorov-Smirnov (K-S) test indicates that the null hypothesis of identical parent populations produces the observed deviation for 30% of the trials. This rather high probability may be misleading, however, because the standard K-S test focuses on the median of the two distributions, which is dominated by the lower $N_{\text{HI}}$ values. From the figure, it is evident that the two distributions only differ in the high $N_{\text{HI}}$ tail of the samples. Integrating the renormalized $\Gamma$-function for the intervening DLAs from $N_{\text{HI}} = 10^{21.5}$ cm$^{-2}$ to infinity, we predict 2.1 absorbers compared against the 6 that are observed with $N_{\text{HI}} > 21.5$. Even if we ignore the uncertainty in the predicted incidence, the Poisson error on six absorbers implies that they differ at only 2 $\sigma$ significance (i.e., 95% c.l.). Therefore, we contend that the figure is suggestive but there is no conclusive evidence for a difference in the shape of $f(N_{\text{HI}}, X)$ for the proximate and intervening DLA systems. Finally, we investigated redshift evolution in the shape of $f(N_{\text{HI}}, X)$ for the PDLAs by splitting the sample at $z = 3$. We found no
5.2. The Incidence of PDLA Systems (\(\ell_{\text{PDLA}}\))

The zeroth moment with respect to \(N\) of the \(\text{H} \, i\) frequency distribution gives the incidence of absorbers along the sight line. Authors traditionally express this quantity per unit redshift, \(\ell(z)\). Of greater interest to the nature of the DLA systems is the incidence per unit absorption distance, \(\ell(X)\). We consider both quantities. It is standard practice to discretely estimate \(\ell(z)\) with a calculation evaluated over a redshift interval \([z_{\text{min}}, z_{\text{max}}]\),

\[
\ell(z) = \frac{m_{\text{PDLA}}}{\sum_{z_{\text{min}} < z < z_{\text{max}}} n(z)},
\]

where \(m_{\text{PDLA}}\) is the number of DLA systems within the redshift interval.

For our evaluation of \(\ell(z)\) and \(\ell(X)\) we include a subtle but important modification. Although we have defined the search path of each quasar to be from \(dv = 0 \, \text{km s}^{-1}\) to \(v_{\text{prox}}\) (eqs. [1] and [3]) for quasars with \(z_{\text{em}} \in [z_{\text{min}}, z_{\text{max}}]\), we also include all of the absorbers with \(dv < 0 \, \text{km s}^{-1}\) in our calculation of \(m_{\text{PDLA}}\). That is, we increment \(m_{\text{PDLA}}\) by 1 for each damped \(\text{Ly}\, \alpha\) system with \(dv < 0 \, \text{km s}^{-1}\) even though we have defined the search path \((\Delta z)\) to have \(dv \geq 0 \, \text{km s}^{-1}\). At first glance, it appears that we will overestimate \(\ell(z)\). We have adopted this formalism, however, to account for the relatively large systematic uncertainties in the quasar redshifts (eq. 4). If these errors are roughly symmetric, then we will have as many PDLAs shifted outside the sample as shifted in at the boundary \(v = v_{\text{prox}}\). Similarly, for any given quasar we will be searching a little more or less redshift path than 3000 km s\(^{-1}\) depending on the sense of the quasar redshift error, but the total search path length will be approximately correct. At the same time, however, we must include all DLA systems with \(dv < 0 \, \text{km s}^{-1}\) to accurately assess \(\ell(z)\).

Figure 5 presents (a) \(\ell(z)\) and (b) \(\ell(X)\) as a function of redshift for the PDLA systems. The curves in each panel correspond to

\[\langle \ell(z) \rangle = 0.6 \exp (-7/z^2),\]

which is a good representation\(^9\) of \(\langle \ell(z) \rangle\) for the intervening DLA systems at \(z > 2\). In fact, a power-law representation of the form

\[\ell(z) \propto (1+z)^{-1}\]

(e.g., Storrie-Lombardi & Wolfe 2000) is no longer a good description of the incidence at high \(z\).

The two panels show similar results. One observes a statistically significant enhancement in the incidence of PDLA systems for \(z = 3\) to \(3.5\) and that the incidence of PDLAs is enhanced yet consistent with the intervening values at other redshifts given statistical uncertainties. Because the representation of \(\ell\) given by Figure 5 may be sensitive to the binning, we also compare the proximate and intervening DLA systems as a function of redshift in histogram form (Fig. 6). Here we have histogrammed the redshifts of the PDLA systems in the full sample and overplotted the predicted number calculated by convolving the redshift search path \(\mathcal{P}(z)\) with the incidence of intervening DLAs (eq. [5]).

If we assume Poisson statistics, we find that the 95% c.l. intervals of the \(z = [2.5, 3]\) and \(z = [3, 3.5]\) do not overlap for the PDLA and intervening systems. Similarly, we find that the 99% c.l. intervals on \(\ell\) for \(z = [2.5, 3.5]\) do not overlap. We conclude, therefore, that the PDLA systems exhibit a higher incidence than the intervening DLAs in the redshift range \(z = [2.5, 3.5]\) but are otherwise consistent with the cosmic average. We attempt to interpret this rather unusual signal in the following section.

A puzzling result from REB06 was that the authors reported an enhancement in \(\ell(z)\) for DLA systems with 3000 km s\(^{-1}\) < \(dv < 6000\) km s\(^{-1}\) which even exceeded that for PDLAs with \(dv < 3000\) km s\(^{-1}\). Such an enhancement is very unlikely to be related to absorber clustering near quasiars. At \(z \approx 3\), \(dv = 3000\) km s\(^{-1}\) corresponds to a comoving distance \(\approx 30\) Mpc \(h^{-1}\).

Even for the high redshift quasar clustering measured by Shen et al. [2007; e.g., \(\xi(r) = (r/r_0)^{-3}\) with comoving \(r_0 \sim 17\) Mpc \(h^{-1}\)]

\[
\begin{array}{c|c|c|c}
\text{Form} & \text{Parameters} & z & \ell(2.2, 5.5) \text{ c.l.} \\
\hline
\text{Single} & \log k_1 & 20.32 \pm 0.04 & 23.56 \pm 0.08 & 23.56 \pm 0.08 \\
\hline
\text{Gamma} & \log k_2 & -2.05^{+0.99}_{-0.11} & -2.21^{+0.19}_{-0.24} & -2.21^{+0.19}_{-0.24} \\
\hline
\end{array}
\]

\(\text{Table 4: Fits to } f(N_{\text{PDLA}} /X)\)

**Note:** The errors reported are one-parameter errors that do not account for correlations among the parameters.

The \(N_{\text{PDLA}}\) parameter reported is a 95% c.l. lower limit.

\(^9\) The function is not properly defined at \(z = 0\), but one could add a small offset to achieve this.
and $\gamma = 2$ at $z \gtrsim 3$] a relatively small enhancement is expected at $\delta v > 3000$ km s$^{-1}$ from the quasar. In Figure 7 we present $\ell(z)$ for 3000 km s$^{-1} < \delta v < 6000$ km s$^{-1}$ adopting (a) the SDSS-DR5 quasar redshifts and (b) our revised values. Although the latter shows a mild enhancement in $\ell(z)$ at $z \approx 3$, the effect is significantly smaller than in REB06. Adopting the revised redshifts, furthermore, we derive $\ell(z)$ values consistent with the cosmic average. We suspect, therefore, that the REB06 result for $v_{\text{prox}} = 6000$ km s$^{-1}$ was predominantly the result of spurious redshifts, although they reached conclusions qualitatively similar to our own when restricting to $\delta v < 3000$ km s$^{-1}$.

REB06 also reported an enhancement in PDLAs of a factor $\ell(z) = 1.4(\ell(z))$ with $\approx 2\sigma$ significance at a mean redshift $z_{\text{abs}} = 3.36$. Our results indicate a larger enhancement and much higher statistical significance at this redshift. Again, the differences are related to our larger sample size and errors in the $z_{\text{em}}$ values reported by the SDSS. We also note that our results more resemble those from Ellison et al. (2002), who had more precisely measured QSO redshifts given the lower median redshift of their sample.

Because errors in the quasar redshifts remain at the level of a few hundred kilometers per second, one must consider whether the enhancement in $\ell(X)$ for $\Delta v < 3000$ km s$^{-1}$ may be spurious. This concern is heightened by the fact that the velocities are one-sided, i.e., ignoring peculiar motions, $\delta v > 0$ km s$^{-1}$. Therefore, if the uncertainties in the quasar redshifts are of the order of a few thousand kilometers per second (i.e., $v_{\text{prox}}$), then one would preferentially scatter PDLAs into the $\delta v < v_{\text{prox}}$ bin from the “infinite” pool of DLAs with $\delta v > v_{\text{prox}}$. By a similar token, if PDLAs do cluster with quasars, then a random redshift error will tend to weaken the clustering signal. With these issues in mind, we have set $v_{\text{prox}}$ to a value large compared to the quasar redshift error and the expected clustering “length.” This approach, however, presumably reduces the signal-to-noise ratio of the clustering signal by including a large interval beyond the clustering length. All of these issues can be better addressed by acquiring infrared spectra of nebular lines to better constrain the quasar redshifts.

### 5.3. The H I Mass Density within $\approx 30$ h$^{-1}$ Mpc of Quasars ($\Omega_\text{HI}^\text{PDLA}$)

The first moment with respect to $N$ of the H I frequency distribution yields the mass density in H I atoms:

$$
\Omega_\text{HI}(X) dX \equiv \frac{\mu m_\text{HI} H_0}{c \rho_c} \int_{N_{\text{min}}}^{N_{\text{max}}} N f(N_{\text{HI}}(X)) dX dN,
$$

where $\mu$ is the mean particle mass per $m_{\text{HI}}$ of the gas (taken to be 1.3), $H_0$ is Hubble’s constant, and $\rho_c$ is the critical mass density. Because the damped Lyα systems dominate this integral (Prochaska & Herbert-Fort 2004; O’Meara et al. 2007) and because they are predominantly neutral, an evaluation of equation (6) from $N_{\text{min}} = 2 \times 10^{20}$ cm$^{-2}$ to infinity gives an accurate estimate of the mass density of neutral gas. For this analysis, we have focused on proximate DLA systems with $\delta v \leq 3000$ km s$^{-1}$, roughly corresponding to a comoving 30 Mpc h$^{-1}$. We refer to this quantity
as $\Omega_g^{PDLA}$, the average mass density of neutral gas measured along an $\approx 30$ Mpc $h^{-1}$ path toward quasars with a median $r$-magnitude of 19.1 mag with standard deviation 0.67 mag.

Following standard practice (e.g., PHW05), we estimate $\Omega_g^{PDLA}$ over a redshift interval with a discrete evaluation:

$$\Omega_g^{PDLA} = \mu m_H H_0 \sum_i N_{H_1} / \Delta X,$$

where the sum is performed over the $N_{H_1}$ measurements of the damped Lyα systems in a given redshift interval with survey path length $\Delta X$. The results are presented in Figure 8 and compared against the mass density for intervening damped Lyα systems, $\Omega_g^{DLa}$, determined from the DR3 sample (PHW05). Similar to the zeroth moment of $f(N_{H_1}, X)$, we find that $\Omega_g^{PDLA}$ is consistent with $\Omega_g^{DLa}$ at $z < 3$ but exceeds $\Omega_g^{DLa}$ at $z \approx 3.5$. Although the uncertainty in $\Omega_g^{PDLA}$ is large, the enhancement over $\Omega_g^{DLa}$ is significant at greater than 95% c.l. in the $z = 3-3.5$ interval.

There are two additional points to emphasize with regards to our estimation of $\Omega_g^{PDLA}$. First, we do not have a large enough sample of proximate DLAs to determine the inevitable break in the $\alpha \approx -2$ power law for $f(N_{H_1}, X)$ observed for $N_{H_1} < 10^{21.3} \text{ cm}^{-2}$. Therefore, our evaluation of $\Omega_g^{PDLA}$ is formally a lower limit at all redshifts. Second, as noted above, we are measuring $\Omega_g^{PDLA}$ along biased sight lines. If bright quasar photons ionize significant quantities of neutral hydrogen gas and do it anisotropically, we will underestimate $\Omega_g^{PDLA}$ if magnitude-limited quasar surveys are biased to these viewing angles. We suspect that the first effect (sample size) is a less than factor of 2 effect because $\Omega_g^{PDLA}$ is only increasing logarithmically with $N_{\text{max}}$, and we consider simple models of the latter effect in § 6.

6. DISCUSSION

In this section we physically interpret the incidence of PDLA systems measured in § 5.2 (see Table 5), by considering two complementary measurements: the clustering of optically thick absorbers around quasars in the transverse direction, measured from close projected pairs of quasars (Hennawi & Prochaska 2007), and the strength and evolution of the autocorrelation function of high-redshift quasars (Shen et al. 2007). Because PDLAs can be detected in absorption against bright background quasars out to $z \approx 5$, their statistics probe the environments of quasars to much higher redshifts than galaxy cross-correlation studies (Adelberger & Steidel 2005; Coil et al. 2007). However, the large ionizing flux emitted by a quasar can ionize the neutral gas in nearby galaxies, thus reducing their absorption cross section (Hennawi & Prochaska 2007). The interpretation of PDLA incidence as a measure of quasar-galaxy clustering is thus complicated by ionization effects. Nevertheless, the physical problem of a quasar illuminating a self-shielding optically thick absorber is very rich and can teach us much about both quasars and high-redshift galaxies.

Following Hennawi & Prochaska (2007) we can describe the increase or decrease in the line density, $\ell(z)$, of proximate DLAs at a velocity separation $v$ from a quasar with the “line-of-sight” correlation function

$$\ell(z, v) = (\ell(z)) [1 + \chi ||(v, \nu)],$$

where $\ell(z)$ represents the cosmic average line density (PHW05) and $\Delta v$ indicates the width of the velocity interval searched. The LOS correlation function is given by an average of the quasar-absorber correlation function, $\xi_{QSO-DLa}(r)$, over a cylinder with cross section $A$ equal to the DLA cross section and extent $\Delta v / aHz$ along the line-of-sight direction. Here $A$ is the scale factor and $H(z)$ is the Hubble constant at redshift $z$. For velocity separations $v$ close to the quasar, $\chi ||$ depends on the size of the absorber cross section, which is unknown. In what follows, we assume a plausible radius of $r_{abs} \equiv (A/\pi)^{1/2} = 20$ kpc. Increasing $r_{abs}$ by a factor of 2 results in a factor of 2 decrease in $\chi ||$ (see Fig. 2 of Hennawi & Prochaska 2007).

Using projected pairs of quasars, Hennawi & Prochaska (2007) measured the cross-correlation between foreground quasars at $z \approx 2.5$ and optically thick $N_{H_1} > 10^{19} \text{ cm}^{-2}$ absorbers, detected in the background quasar spectra. Assuming a power-law shape for the quasar-absorber correlation function, they measured $r_0 = 9.2^{+1.2}_{-1.7} \text{ h}^{-1} \text{ Mpc}$ for $\gamma = 1.6$, or $r_0 = 5.8^{+1.0}_{-0.6} \text{ h}^{-1} \text{ Mpc}$ for $\gamma = 2$. This measurement of the transverse clustering of absorbers around quasars should be commensurate with the line-of-sight clustering probed by the incidence of PDLA systems, provided that the clustering pattern of absorbers around quasars is isotropic. However, Hennawi & Prochaska (2007) argued that the strength of the transverse clustering predicts that $\approx 50\%$ of all quasars should show a $N_{H_1} > 10^{19} \text{ cm}^{-2}$ absorber within $\Delta v < 3000 \text{ km s}^{-1}$, which is not observed (O’Meara et al. 2007). Thus, the transverse clustering overpredicts the number of absorbers along the line of sight by a large factor, or equivalently the clustering pattern is highly anisotropic. The most plausible physical explanation is that the transverse direction is less likely to be illuminated by ionizing photons than the line of sight, due to either anisotropic emission, or variability of the quasar emission on timescales short compared to the transverse light crossing time ($\approx 5 \times 10^5$ yr). We revisit this issue of anisotropic clustering with the statistics of PDLAs below.

Shen et al. (2007) recently quantified the clustering of high-redshift (2.9 $\leq z \leq 5.4$) quasars and measured a comoving autocorrelation length of $r_0 = 16.9 \pm 1.7 \text{ h}^{-1} \text{ Mpc}$ for quasars in the redshift range $2.9 \leq z \leq 3.5$, and an even stronger $r_0 = 24.3 \pm 2.4 \text{ h}^{-1} \text{ Mpc}$ for $3.5 \leq z \leq 5.4$ quasars. High-redshift quasars are thus much more strongly clustered than their $z \approx 2$ counterparts, which have $r_0 \approx 7.5 \text{ h}^{-1} \text{ Mpc}$ (see, e.g., Porciani et al. 2004; Croom et al. 2005; Porciani & Norberg 2006), and the evolution of the quasar clustering strength with redshift is extremely

### Table 5

**Summary of Results**

| $z$       | $m_{PDLA}$ | $\Delta z$ | $\ell_{PDLA}(z)$ | $\Delta X$ | $\ell_{PDLA}(X)$ | $\Omega_g^{PDLA}$ ($\times 10^{-3}$) |
|-----------|------------|------------|-------------------|------------|------------------|--------------------------------------|
| [2.2, 2.5]| 8          | 48.5       | 0.165 $^{+0.081}_{-0.072}$ | 158.1      | 0.051 $^{+0.025}_{-0.031}$ | 0.56 $^{+0.23}_{-0.18}$ |
| [2.5, 3.0]| 22         | 59.6       | 0.360 $^{+0.077}_{-0.078}$ | 206.6      | 0.107 $^{+0.022}_{-0.023}$ | 1.32 $^{+0.46}_{-0.37}$ |
| [3.0, 3.5]| 48         | 72.0       | 0.666 $^{+0.111}_{-0.095}$ | 265.5      | 0.181 $^{+0.036}_{-0.028}$ | 2.99 $^{+0.75}_{-0.69}$ |
| [3.5, 5.2]| 29         | 59.2       | 0.490 $^{+0.199}_{-0.099}$ | 237.8      | 0.122 $^{+0.027}_{-0.023}$ | 2.05 $^{+0.67}_{-0.52}$ |

This redshift limit is set by the small number of quasars with $z > 5$ (Richards et al. 2006).
rapid. Naively, we expect this to drive a rapid evolution in the cross-correlation of quasars with DLAs.

Our strategy for comparing the PDLA clustering to these complementary measurements is to normalize the quasar-DLA cross-correlation strength to the transverse Hennawi & Prochaska (2007) result at \( z = 2.5 \) and assume that the clustering of DLAs does not evolve with redshift but that the quasar clustering evolves as measured by Shen et al. (2007). Specifically, we use the relation

\[
\xi_{\text{QSO-DLA}}(r,z) = \xi_{\text{QSO-QSO}}(r,z)\xi_{\text{DLA-DLA}}(r) \tag{9}
\]

to determine the parameters of the \( \xi_{\text{DLA-DLA}} \) and propagate errors according to those quoted by both measurements. The use of equation (9) presumes that the relative bias between quasars and DLAs is deterministic, i.e., that the overdensity of quasars at a given scale determines the overdensity of DLAs on the same scale (and vice versa). On the other hand, if variables other than the distribution of dark matter halos influence where DLAs and quasars form, there will be scatter in the correlation between their respective overdensities, giving rise to a stochastic relative bias (Dekel & Lahav 1999; Blanton 2000). Our assumption of deterministic bias is partly justified by the measurement of Hennawi & Prochaska (2007), who directly measured the cross-correlation function between quasars and sub-DLAs. As we will see, this measurement agrees with the estimate from equation (9).

Shen et al. (2007) measured the autocorrelation function of quasars in two redshift bins \( 2.9 < z < 3.5 \) and \( z > 3.5 \), very similar to the two high-redshift bins in this work. Quasar clustering has not yet been measured in the redshift range \( 2.1 < z < 2.9 \), so we linearly interpolate between the Shen et al. (2007) result and the redshift evolution measured by Porciani & Norberg (2006).\(^{12} \)

A few limitations to our approach should be noted. First, by assuming that the CLA clustering does not evolve, we might overestimate (underestimate) the strength of the quasar-DLA cross-correlation function if DLA galaxies are less (more) clustered at high redshift. However, Adelberger et al. (2005) found that the clustering of LGBs is very nearly constant in the range \( r_0 \sim 4-5 \ h^{-1} \) Mpc over the redshift range \( 1.4 \leq z \leq 3.5, \) and Ouchi et al. (2004) similarly measured the correlation lengths of \( 3.5 \leq z \leq 5.2 \) LGBs and found a correlation length of \( r_0 \sim 5 \ h^{-1} \) Mpc that was nearly constant with redshift. In light of evidence that DLA galaxies are drawn from a similar (but fainter) galaxy population as spectroscopically selected LGBs (Möller et al. 2002; Schaye 2001), it is reasonable to assume that DLA clustering does not evolve significantly. Second, the Hennawi & Prochaska (2007) measurement was for all absorbers with \( N_{\text{H_1}} > 10^{19} \) cm\(^{-2} \), so by applying that measurement to the DLAs \( (N_{\text{H_1}} \geq 2 \times 10^{20} \) cm\(^{-2} \) ) we implicitly assume that the clustering of absorbers is independent of column density.\(^{12} \) Finally, it is conceivable that the (Hennawi & Prochaska 2007) cross-correlation strength is overestimated because of line blending of systems near the column density threshold \( (N_{\text{H_1}} > 10^{19} \) cm\(^{-2} \) ), which results in a “Malmquist”-type bias because the line density \( f(z) \) of absorbers is a relatively steep function (O’Meara et al. 2007) of column density limit.

To address these issues we explore another avenue for estimating the autocorrelation of \( \xi_{\text{DLA-DLA}} \) in equation (9). Namely,

\(^{11} \)Porciani & Norberg fit a shallower slope \( (\gamma = 1.8) \) than Shen et al. \( (\gamma = 2) \). For simplicity we assume a single slope \( \gamma = 2 \) and commensurately adjust the correlation length measured by Porciani & Norberg such that our resulting steeper correlation function matches their shallower measurement \( (\gamma = 1.8) \) at \( 5 \ h^{-1} \) Mpc.\(^{11} \)

\(^{12} \)This is a reasonable assumption if absorbers with \( N_{\text{H_1}} \approx 10^{19} \) cm\(^{-2} \) arise from material at larger impact parameters from DLA systems (e.g., Maller et al. 2003).

Cooke et al. (2006) used photometrically selected LBGs in the vicinity of DLAs to measure the cross-correlation between LBGs and DLAs at \( z \sim 3 \). Assuming \( \gamma = 1.6 \), they measured \( r_0 = 2.93^{+1.2}_{-0.6} \) for the LBG-DLA cross-correlation and \( r_0 = 3.32^{+1.4}_{-0.6} \) for the LBG autocorrelation. From \( \xi_{\text{DLA-DLA}} = (\xi_{\text{DLA-LBG}}/\xi_{\text{LBG-LBG}})^{1/2} \), we deduce the autocorrelation of DLAs to be \( r_0 = 2.6^{+0.7}_{-0.6} \) h\(^{-1} \) Mpc \( (\gamma = 1.6) \), which can then be used in equation (9), again assuming that the DLA clustering does not evolve with redshift.

Our measurement of the evolution of the overdensity of PDLAs near quasars \( (1 + \chi_L) \) (see eq [9]) to those implied by other measurements. The data points show our measurements of the line-of-sight correlation function from the abundance of PDLAs, where the horizontal error bars indicate the size of the redshift bins used. The solid curve shows the line-of-sight correlation function prediction obtained by combining the Shen et al. (2007) clustering results with the Hennawi & Prochaska (2007) transverse quasar-absorber clustering measurement for \( \gamma = 2 \). The upper striped region illustrates \( 1 \sigma \) error from combining these results. The dashed curve shows the same quantity, but using the Hennawi & Prochaska (2007) measurement with a shallower slope of \( \gamma = 1.6 \) (the \( 1 \sigma \) error region is comparable to the upper striped region but not shown for clarity). The dotted curve and lower striped region are the line-of-sight correlation function and corresponding \( 1 \sigma \) error when we combine the Shen et al. (2007) clustering results with DLA autocorrelation implied by the Cooke et al. (2006) measurements. The cross-hatching indicates the overlap of the error regions and illustrates that the Hennawi & Prochaska (2007) results and Cooke et al. (2006) measurement are consistent within the errors. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 9.—Comparison of the evolution of the overdensity of PDLAs near quasars \( (1 + \chi_L) \) (see eq [9]) to those implied by other measurements. The data points show our measurements of the line-of-sight correlation function from the abundance of PDLAs, where the horizontal error bars indicate the size of the redshift bins used. The solid curve shows the line-of-sight correlation function prediction obtained by combining the Shen et al. (2007) clustering results with the Hennawi & Prochaska (2007) transverse quasar-absorber clustering measurement for \( \gamma = 2 \). The upper striped region illustrates \( 1 \sigma \) error from combining these results. The dashed curve shows the same quantity, but using the Hennawi & Prochaska (2007) measurement with a shallower slope of \( \gamma = 1.6 \) (the \( 1 \sigma \) error region is comparable to the upper striped region but not shown for clarity). The dotted curve and lower striped region are the line-of-sight correlation function and corresponding \( 1 \sigma \) error when we combine the Shen et al. (2007) clustering results with DLA autocorrelation implied by the Cooke et al. (2006) measurements. The cross-hatching indicates the overlap of the error regions and illustrates that the Hennawi & Prochaska (2007) results and Cooke et al. (2006) measurement are consistent within the errors. [See the electronic edition of the Journal for a color version of this figure.]
A discrepancy is apparent between the predictions in Figure 9, which are driven by the strength of the quasar autocorrelation function and its rapid redshift evolution, and the relatively modest clustering of PDLAs around quasars and lack of evolution, measured here. This disagreement provides compelling evidence for the hypothesis that the ionizing flux from quasars photoevaporates H i in nearby DLA galaxies, thus reducing their cross section for DLA absorption. Hennawi & Prochaska (2007) used a simple photoevaporation model to show that optically thick absorbers with $n_H > 0.1$ cm$^{-3}$ will be photoevaporated if they lie within $\sim$1 Mpc of a luminous quasar, so our results are sensible on physical grounds.

The decrease in the number of optically thin Ly$\alpha$ forest absorption lines in the vicinity of quasars, known as the proximity effect, has been detected and is well studied (Bajtlik et al. 1988; Scott et al. 2000; Faucher-Giguere et al. 2007). The factor of $\sim$5–10 discrepancy between the predicted clustering results and the data in Figure 9 provides compelling evidence that a similar proximity effect exists for optically thick absorption-line systems. However, according to Hennawi & Prochaska (2007) there is no transverse proximity effect for optically thick absorbers, which gains further credibility in light of the null detections of the transverse effect in the (optically thin) Ly$\alpha$ forest (Crotts 1989; Dobrzycki & Bechtold 1991; Fernandez-Soto et al. 1995; Liske & Williger 2001; Schirber et al. 2004; Croft 2004; but see Worseck & Wisotzki 2006), although these transverse studies are all based on only a handful of projected pairs. Both the optically thin results and our result for optically thick systems can be explained if the transverse direction is less likely to be illuminated by ionizing photons than the line of sight, either because the emission is anisotropic or because the foreground quasar varies on timescales short compared to the transverse light crossing time ($\sim$5 $\times$ 10$^5$ yr; see Hennawi & Prochaska 2007 for a detailed discussion of both).

We use a toy model to illustrate how quasar-absorber clustering can be used to constrain the physical properties of DLAs following Hennawi & Prochaska (2007), who introduced a photoevaporation criterion for optically thick absorbers illuminated by quasars, motivated by the work of Bertoldi (1989). This criterion allows us to compute a minimum distance from the quasar, as a function of volume density, at which a DLA can self-shield against photoevaporation. In this context, the curves in Figure 9 represent predictions for the intrinsic clustering of DLAs around quasars in the absence of ionization effects. Because proximate absorbers lie along the line of sight, they must be exposed to the quasars’ ionizing flux, and we can calculate the reduction in the clustering strength because of photoevaporation (see Hennawi & Prochaska 2007 for details). The solid, dashed, and dotted curves in Figure 10 represent predictions from the same measurements shown in Figure 9, but after taking photoevaporation into account using this simple approach. We used a volume density of hydrogen of $n_H = 0.1$ cm$^{-3}$ and assumed that the quasar had an average $i$-band magnitude $i = 19.1$, which is the median of our PDLA sample. Although crude, this simple model illustrates how the density distribution in DLAs can be measured by comparing the abundance of PDLAs to the intrinsic quasar-DLA clustering, deduced either from the transverse quasar-DLA clustering or by combining independent measurements of quasar and DLA clustering.

7. SUMMARY

We surveyed the spectra of 5938 SDSS quasars in the redshift range $2.2 < z < 5$ for proximate DLAs within 3000 km s$^{-1}$ of the quasar emission redshift and presented the largest sample (108 systems) of PDLAs uncovered to date. Robust systemic redshifts of the quasars hosting these PDLAs were computed using a redshift estimator that accounts for the relative shifts between quasar emission lines and the systemic frame, and that ignores the Ly$\alpha$ emission line, which can be entirely absorbed for quasars with PDLAs. These improved redshifts allowed us to measure the abundance and distribution of PDLAs near quasars. The primary conclusions of this study are:

1. There is suggestive evidence that the $N_H$, values of the PDLA population are not drawn from the same parent population as intervening DLAs systems. Specifically, the PDLA sample does not show evidence for a break from a single power-law model. However, the statistical significance of the difference between the PDLA column density distribution and the underlying distribution of intervening DLA systems is only at the 2 $\sigma$ level (i.e., 95% c.l.).

2. PDLA systems exhibit a statistically significant, higher incidence than the intervening DLA's in the redshift range $z < 2.5, 3.5$. The incidence is also enhanced relative to the cosmic average at lower ($z < 2.2, 2.5$) and higher ($z > 3.5, 5.0$) redshifts, but this result is not statistically significant.

3. The average mass density measured along an $\approx$30 Mpc $h^{-1}$ path toward the quasars that we surveyed, $\Omega_{DLA}^{PDLA}$, is consistent with the cosmic average, $\Omega_{DLA}$, at $z < 3.0$ and $>3.5$. In the redshift interval $z \in [3.0, 3.5]$ an enhancement in $\Omega_{DLA}^{PDLA}$ is detected at greater than 95% c.l. with central value $\Omega_{DLA}^{PDLA} = 2-3$ times $\Omega_{DLA}$.

4. A comparison of the strength of the quasar autocorrelation function and its rapid redshift evolution, to the relatively modest clustering of PDLAs around quasars and a lack of significant evolution, provides compelling evidence for the hypothesis that the ionizing flux from quasars photoevaporates H i in nearby DLA galaxies, thus reducing their cross section for DLA absorption (Hennawi & Prochaska 2007).

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