QUASARS PROBING QUASARS. II. THE ANISOTROPIC CLUSTERING OF OPTICALLY THICK ABSORBERS AROUND QUASARS

JOSEPH F. HENNAWII,1,2 AND JASON X. PROCHASKA3

Received 2006 June 5; accepted 2006 September 20

ABSTRACT

With close pairs of quasars at different redshifts, a background quasar sight line can be used to study a foreground quasar’s environment in absorption. We used a sample of 17 Lyman limit systems with column density $N_{\text{HI}} > 10^{19}$ cm$^{-2}$ selected from 149 projected quasar pair sight lines to investigate the clustering pattern of optically thick absorbers around luminous quasars at $z \sim 2.5$. Specifically, we measured the quasar-absorber correlation function in the transverse direction and found a comoving correlation length of $r_0 = 9.2^{+1.5}_{-1.3} h^{-1}$ Mpc (comoving), assuming a power-law correlation function $\xi \propto r^{-\gamma}$, with $\gamma = 1.6$. Applying this transverse clustering strength to the line of sight, would predict that $~15\%-50\%$ of all quasars should show a $N_{\text{HI}} > 10^{19}$ cm$^{-2}$ absorber within a velocity window of $\Delta v < 3000$ km s$^{-1}$. This overpredicts the number of absorbers along the line of sight by a large factor, providing compelling evidence that the clustering pattern of optically thick absorbers around quasars is highly anisotropic. The most plausible explanation for the anisotropy is that the transverse direction is less likely to be illuminated by ionizing photons than the line of sight, and that absorbers along the line of sight are being photoevaporated. A simple model for the photoevaporation of absorbers subject to the ionizing flux of a quasar is presented, and it is shown that absorbers with volume densities $n_\text{HI} \leq 0.1$ will be photoevaporated if they lie within $\sim 1$ Mpc (proper) of a luminous quasar. Using this simple model, we illustrate how comparisons of the transverse and line-of-sight clustering around quasars can ultimately be used to constrain the distribution of gas in optically thick absorption-line systems.

Subject headings: intergalactic medium — quasars: absorption lines — quasars: general — surveys

Online material: color figures

1. INTRODUCTION

Although optically thick absorption-line systems, i.e., Lyman limit systems (LLSs) and damped Ly$\alpha$ systems (DLAs), are detected as the strongest absorption lines in quasar spectra, the two types of objects, quasars and absorbers, play rather different roles in the evolution of structure in the universe. The hard ultraviolet radiation emitted by luminous quasars gives rise to the ambient extragalactic ultraviolet (UV) background (see e.g., Haardt & Madau 1996; Miralda-Escudé 2003; Meiksin 2005) responsible for maintaining the low neutral fraction of hydrogen ($\sim 10^{-6}$) in the intergalactic medium (IGM), established during reionization. However, high column density absorbers represent the rare locations where the neutral fractions are much larger. Gas clouds with column densities $\log N_{\text{HI}} > 17.2$ are optically thick to Lyman continuum ($\tau_{\text{LL}} \gtrsim 1$) photons, giving rise to a neutral interior self-shielded from the extragalactic ionizing background. In particular, the damped Ly$\alpha$ systems dominate the neutral gas content of the universe (Prochaska et al. 2005), which is the primary reservoir for the formation of stars observed in local galaxies.

One might expect optically thick absorbers to be absent at small separations from luminous quasars. For example, a quasar at $z = 2.5$ with magnitude $r = 19$ emits a flux of ionizing photons that is 130 times higher than that of the extragalactic UV background at an angular separation of $60^\circ$, corresponding to a proper distance of $340$ $h^{-1}$ kpc. Indeed, the decrease in the number of “optically thin” absorption lines ($\log N_{\text{HI}} < 17.2$, hence $\tau_{\text{LL}} \lesssim 1$) in the vicinity of quasars, known as the “proximity effect” (Bajtlik et al. 1988), provides a measurement of the UV background (Scott et al. 2000). If nature provides a nearby background quasar sight line, one can also study the “transverse proximity effect,” which is the expected decrease in absorption in a “background” quasar’s Ly$\alpha$ forest caused by the transverse ionizing flux of a “foreground” quasar. The transverse effect has yet to be detected, in spite of many attempts (Croft 1989; Dobrzycki & Bechtold 1991; Fernandez-Soto 1995; Liske & Williger 2001; Schirber et al. 2004; Croft 2004; but see Jakobsen et al. 2003).

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. 2006b), although these measurements of quasar galaxy clustering are mostly limited to low redshifts $\leq 1.0$. Recently, Adelberger & Steidel (2005, hereafter AS05) measured the clustering of Lyman break galaxies (LBGs) around luminous quasars in the redshift range $2 \lesssim z \lesssim 3.5$ and found a best-fit correlation length of $r_0 = 4.7$ $h^{-1}$ Mpc ($\gamma = 1.6$), very similar to the auto-correlation length of $z \sim 2$–3 LBGs (Adelberger et al. 2003). Cooke et al. (2006) recently measured the clustering of LBGs around DLAs and measured a best-fit $r_0 = 2.9$ $h^{-1}$ Mpc with $\gamma = 1.6$, but with large uncertainties (see also Gawiser et al. 2001; Bouche & Lowenthal 2004). If LBGs are clustered around quasars and DLAs, might we expect optically thick absorbers 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 (Schaye 2001; Møller et al. 2002).

Clues to the clustering of optically thick absorbers around quasars come from “proximate DLAs,” which have absorber redshifts within $3000$ km s$^{-1}$ of the emission redshift of the quasars.

1 Department of Astronomy, University of California, Berkeley, CA; joeh@berkeley.edu.
2 Hubble Fellow.
3 Department of Astronomy and Astrophysics, University of California Observatories/Lick Observatory, University of California, Santa Cruz, CA; xavier@ucolick.org.
(see e.g., Möller et al. 1998). Recently, J. X. Prochaska et al. (2007, in preparation) compared the line density of proximate DLAs in the Sloan Digital Sky Survey (SDSS) Data Release 5 quasar catalog to the average number density of DLAs in the universe (Prochaska et al. 2005) and found that the abundance of DLAs is enhanced by a factor of $\sim 1.4$ near quasars. A similar study by Russell et al. (2006; see also Ellison et al. 2002) measured a comparable enhancement, which they attributed to the clustering of DLA galaxies around quasars.

Projected pairs of quasars with small angular separations ($\theta \lesssim 5\arcmin$) but different redshifts can also be used to study the clustering of absorbers around quasars. In this context, clustering is manifest as an excess probability, above the cosmic average, of detecting an absorber in the neighboring background quasar spectrum near the redshift of the foreground quasar. In the first of this series of four papers on optically thick absorbers near quasars (Hennawi et al. 2006b, hereafter Paper I), we used background quasar sight lines to search for optically thick absorption in the vicinity of foreground quasars: 149 projected quasar pairs were systematically surveyed for Lyman limit Systems (LLSs) and Damped Ly$\alpha$ systems (DLAs) in the vicinity of $1.8 < z < 4.0$ luminous foreground quasars. A sample of 27 new absorbers were uncovered with transverse separations $R < 5 \, h^{-1} \, \text{Mpc}$ (comoving) from the foreground quasars, of which 17 were super-LLSs with $N_{\text{HI}} > 10^{19} \, \text{cm}^{-2}$.

The distribution of foreground quasar redshifts, transverse separations, and ionizing flux ratios probed by the projected pair sight lines studied in Paper I are illustrated in Figure 1. The filled symbols outlined in black indicate the sight lines that have an absorption-line system with $N_{\text{HI}} > 10^{19} \, \text{cm}^{-2}$ within a velocity interval of $|\Delta v| = 1500 \, \text{km} \, \text{s}^{-1}$ of the foreground quasar redshift, and the open symbols represent sight lines with no such absorber. The line density of absorbers per unit redshift at $z \sim 2.5$ with column densities $N_{\text{HI}} > 10^{19} \, \text{cm}^{-2}$ is $dN/dz \approx 0.8$ (O’Meara et al. 2007), which implies that the expected number of “random” quasar-absorber coincidences within $|\Delta v| = 1500 \, \text{km} \, \text{s}^{-1}$ is $\sim 3\%$. The expected number of random quasar-absorber associations in the sample of 149 sight lines is $\langle N \rangle = 4.4$, whereas 17 systems were discovered in Paper I—compelling evidence for clustering.

This clustering is particularly conspicuous on small scales: out of eight sight lines with $R < 500 \, h^{-1} \, \text{kpc}$, four quasar-absorber pairs were discovered, which implies a small-scale covering factor of $\sim 50\%$, whereas $\langle N \rangle = 0.18$ would have been expected at random. This excess of $\sim 25$ over random may not come as a surprise when one considers that galaxies are strongly clustered around quasars on small scales. However, the light from every isolated quasar in the universe traverses these same small scales on the way to Earth. Naively, we would then expect a comparable covering factor of $N_{\text{HI}} > 10^{19} \, \text{cm}^{-2}$ super-LLSs along the line of sight, which is definitely not observed to be the case.

How can we quantify the clustering of absorbers around quasars? How do we compare the transverse clustering pattern to the number of proximate absorbers observed along the line of sight? What can the quasar-absorber clustering pattern teach us about quasars and absorbers? These questions are addressed in this second paper of the series. We briefly review the Paper I survey of projected quasar pairs and discuss the quasar-absorber sample in § 2. A formalism for quantifying the line of sight and transverse clustering of absorbers around quasars is presented in § 3. In § 4 we introduce a maximum likelihood technique for estimating the quasar-absorber correlation function, which we use to measure the clustering of our quasar-absorber sample in § 5. Our measurement of the transverse clustering is used to predict the expected number of proximate absorption-line systems that should be observed along the line of sight in § 6. In § 7, we introduce a simple analytical model for the photoevaporation of optically thick absorbers by quasars, which is used to illustrate how comparisons of the line-of-sight and transverse clustering can constrain the distribution of gas in optically thick absorbers. We summarize and discuss our results in § 8.

Paper III of this series (J. F. Hennawi et al. 2007, in preparation) investigates fluorescent Ly$\alpha$ emission from our quasar-absorber pairs, and echelle spectra of several of the quasar-LLS systems published here are analyzed in Paper IV (J. X. Prochaska & J. F. Hennawi 2007, in preparation). Throughout this paper we use the best-fit $WMAP$ (only) cosmological model of Spergel et al. (2003) with $\Omega_m = 0.270$, $\Omega_{\Lambda} = 0.73$, and $h = 0.72$. Unless otherwise specified, all distances are comoving. It is helpful to remember that in the chosen cosmology, at a redshift of $z = 2.5$, an angular separation of $\Delta \theta = 1''$ corresponds to a comoving transverse separation of $R = 20 \, h^{-1} \, \text{kpc}$, and a velocity $\Delta v = 1500 \, \text{km} \, \text{s}^{-1}$.
difference of 1500 km s\(^{-1}\) corresponds to a radial redshift space distance of \(s = 15 \, h^{-1} \text{ Mpc}\). For a quasar at \(z = 2.5\), with an SDSS magnitude of \(r = 19\), the flux of ionizing photons is 130 times higher than the ambient extragalactic UV background at an angular separation of 60'' (comoving \(R = 1.2 \, h^{-1} \text{ Mpc}\)). Finally, we use the terms “optically thick absorbers” and “LLSs” interchangeably, both referring to quasar absorption-line systems with \(\log N_{\text{HI}} > 17.2\), making them optically thick at the Lyman limit \((\tau_{\text{LL}} \gtrsim 1)\).

### 2. QUASAR-ABSORBER SAMPLE

In this section we briefly summarize the quasar-absorber sample and the parent sample of projected pairs from which it was selected; for full details see Paper I. In § 5 we quantify the clustering of absorbers around quasars in the transverse direction by comparing the number of quasar-absorber pairs discovered to the number from random expectation. Although lower column density systems were published in Paper I, we focus here on absorbers with \(N_{\text{HI}} > 10^{19} \, \text{cm}^{-2}\), or so called super-LLSs. This choice reflects a variety of concerns. First, we wanted to maximize the number of quasar-absorber pairs; had we restricted consideration to only DLAs we would have been left with five systems. Second, this is the lowest column density at which we believe we can identify a statistical sample of absorbers with the moderate resolution spectra used in Paper I. Finally, the column density distribution of optically thick absorption-line systems has been determined for \(\log N_{\text{HI}} > 19\) (Péroux et al. 2005; O’Meara et al. 2007), whereas it is unknown at the lower column densities \(17.2 \leq \log N_{\text{HI}} \leq 19\).

Modern spectroscopic surveys select against close pairs of quasars because of fiber collisions. For the SDSS, the finite size of optical fibers implies only one quasar in a pair with separation <55'' can be observed spectroscopically on a given plate,\(^5\) and a slightly smaller limit (<30'') applies for the Two Degree Field Quasar Survey (2QZ; Croom et al. 2004). Thus, for subarcminute separations, additional spectroscopy is required both to discover companions around quasars and to obtain spectra of sufficient quality to search for absorption-line systems. For wider separations, projected quasar pairs can be found directly in the SDSS spectroscopic quasar catalog. Hennawi et al. (2006a) used the 3.5 m telescope at Apache Point Observatory (APO) to spectroscopically confirm a large sample of photometrically selected close quasar pair candidates and published the largest sample of projected quasar pairs in existence.

In Paper I we combined high signal-to-noise ratio (S/N) moderate resolution spectra of the closest Hennawi et al. (2006a) projected pairs, obtained from Gemini, Keck, and the MMT, with a large sample of wider separation pairs from the SDSS spectroscopic survey. The Keck, Gemini, and MMT spectra were all of sufficient S/N to detect absorbers with column densities \(N_{\text{HI}} > 10^{19} \, \text{cm}^{-2}\), and a S/N criterion was used to isolate the SDSS projected pair sight lines for which such an absorber could be detected in the background quasar spectrum. We considered all projected quasar pair sight lines that had a comoving transverse separation of \(R < 5 \, h^{-1} \text{ Mpc}\), a redshift separation \(\Delta z \geq 2500 \, \text{km s}^{-1}\) between the foreground and background quasar (to exclude physical binaries), and which satisfied our S/N criteria, and we arrived at a total of 149 projected pair sight lines in the redshift range \(1.8 < z < 4.0\).

\(^5\) An exception to this rule exists for a fraction (\~30\%) of the area of the SDSS spectroscopic survey covered by overlapping plates. Because the same area of sky was observed spectroscopically on more than one occasion, there is no fiber collision limitation.

A systematic search for optically thick absorbers with redshifts within \(|\Delta z| < 1500 \, \text{km s}^{-1}\) of the foreground quasars was conducted by visually inspecting the 149 projected pair sight lines, where the velocity window was chosen to bracket the uncertainties in the foreground quasars’ systemic redshift (see e.g., Richards et al. 2002 and § 4 of Paper I). Voigt profiles were fit to systems with significant Ly\(\alpha\) absorption to determine the H\(\text{I}\) column densities. We uncovered 27 new quasar absorber pairs with column densities \(17.2 < \log N_{\text{HI}} < 20.9\) and transverse comoving distances \(71 \, h^{-1} \, \text{kpc} < \langle R \rangle < 5 \, h^{-1} \, \text{Mpc}\) from the foreground quasars, of which 17 were super-LLSs with \(\log N_{\text{HI}} > 19\). The mean redshift of the foreground quasar in the parent sample was \((z) = 2.47\) and that of the 17 quasar–super-LLS pairs was \((z_{\text{abs}}) = 2.55\).

The completeness and false-positive rate of the Paper I survey are a significant source of concern. Prochaska et al. (2005) demonstrated that the spectral resolution (FWHM \(\approx 150 \, \text{km s}^{-1}\)) and S/N of the SDSS spectra are well suited to constructing a complete (\~95\%) sample of DLAs (\(\log N_{\text{HI}} > 20.3\)) at \(z > 2.2\); however, the completeness at the lower column densities \(\log N_{\text{HI}} > 19\) considered here has not been systematically quantified. Furthermore, aggressive S/N criteria were employed in Paper I in order to gather a sufficient number of projected quasar pairs. Line blending can significantly depress the continuum near the Ly\(\alpha\) profile and mimic a damping wing, biasing column density measurements high or giving rise to false positives. Any statistical study will thus suffer from a “Malmquist”-type bias because line blending biases lower column densities upward, and the line density of absorbers \(dn/dz\) is a steep function of column density limit.

Based on visually inspecting the 149 background quasar spectra and a comparison with echelle data for three systems, we estimated that the Paper I survey was \~90\% complete for \(\log N_{\text{HI}} > 19.3\) for all the Keck/Gemini/MMT spectra and \~3/4 of the SDSS spectra, which accounts for about 125 of the 149 spectra searched. To address the false-positive rate, we compared with echelle data for three systems and found that our column density was overestimated by \~2.5 \(\sigma\) for one system, raising it above the super-LLS (\(\log N_{\text{HI}} > 19\)) threshold. However, this absorber was located blueward of the quasars Ly\(\beta\) emission line, in a part of the spectrum “crowded” by the presence of both the Ly\(\alpha\) and Ly\(\beta\) forests. A more careful examination of the completeness and false-positive rate of super-LLSs identified in spectra of the resolution and S/N used in Paper I is definitely warranted. In § 5 we explore how our clustering measurement changes if we discard systems within \(\approx 1 \, \sigma\) of the \(\log N_{\text{HI}} = 19\) threshold.

Relevant quantities for the super-LLS–quasar pairs that are used in our clustering analysis are given in Table 1. The distribution of foreground quasar redshifts, transverse separations, and ionizing flux ratios probed by all of our projected pair sight lines is illustrated in Figure 1. The filled symbols outlined in black indicate the sight lines that have an absorption-line system near the foreground quasar with \(\log N_{\text{HI}} > 19\) (see Table 1), and open symbols are sight lines with no such absorber.

### 3. QUANTIFYING QUASAR-ABSORBER CLUSTERING

In the absence of clustering, the line density of absorption-line systems per unit redshift above the column density threshold \(N_{\text{HI}}\) is given by the cosmic average

\[
\left\langle \frac{dN}{dz} \right\rangle (\log N_{\text{HI}}, z) = n A_{\text{cont}} \frac{c}{H(z)},
\]

where \(n\) is comoving number density of the galaxies or objects that give rise to absorption-line systems, \(A\) is their absorption...
cross section (in comoving units), \( f_{\text{cov}} \), is the covering factor, and \( H(z) \) is the Hubble constant. Note that the line density is degenerate with respect to the combination \( n_{\text{H}1}/f_{\text{cov}} \), and only their product can be determined by measuring the abundance of absorption-line systems.

At an average location in the universe, the probability of finding an absorber in a background quasar spectrum within the redshift interval \( \Delta z = 2(1 + z)\Delta v/c \), corresponding to a velocity interval \( \Delta v \), is simply \( P = \langle dN/dz \rangle \Delta z \). For a projected pair of quasars, clustering around the foreground quasar will increase the probability of finding an absorber in the background quasar spectrum in the vicinity of the foreground quasar, whereas the foreground quasar radiation field could reduce this enhancement by photoevaporating absorption systems. If the quasar sight lines have a comoving transverse separation \( R \), and assuming that one searches a velocity interval \( \pm \Delta v \) about the foreground quasar redshift (because of redshift uncertainties), we can express the increase in line density near the foreground grounds in terms of a transverse correlation function \( \chi_\perp (R) \) as

\[
\frac{dN}{dz} = \left( \frac{dN}{dz} \right) [1 + \chi_\perp (R, \Delta v)],
\]

where \( \chi_\perp (R, \Delta v) \) is given by an average of the three-dimensional quasar-absorber correlation function, \( \xi_{\text{QA}}(r) \), over a cylinder with volume \( V = A(2\Delta v/aH(z)) \), where, \( a \) is the scale factor and \( 2\Delta v(1 + z)H(z) \) is the length of the cylinder in the line-of-sight direction. We can thus write

\[
\chi_\perp (R) = \frac{1}{V} \int_V dV \xi_{\text{QA}}(r) \\
\approx \frac{aH(z)}{2\Delta v} \int_{-\Delta v/aH(z)}^{\Delta v/aH(z)} dZ \xi_{\text{QA}}(\sqrt{R^2 + Z^2}),
\]

where \( Z \) is a comoving distance in redshift space. The last approximation in equation (4) assumes that the volume average over the cylinder can be replaced by the line average along the line-of-sight direction, which is valid provided that we are in the "far-field" limit, i.e., the transverse separation is much larger than the diameter of the cylinder \( R \gg A^{1/2} \). Thus, provided we consider distances \( R \) much larger than the dimension of the absorber, the transverse clustering is independent of the absorption cross section.

For proximate absorbers along the line of sight, we can similarly define a line-of-sight correlation function

\[
\frac{dN}{dz} = \left( \frac{dN}{dz} \right) [1 + \chi_\parallel (\Delta v)],
\]

where

\[
\chi_\parallel (\Delta v) = \frac{aH(z)}{A\Delta v} \int_{Z_{\text{cut}}}^{\Delta v/aH(z)} dZ \int dA \xi_{\text{QA}}(r).
\]

The lower limit of the radial integration is set to \( Z_{\text{cut}} \), a cutoff that is introduced to parameterize our ignorance of the geometry of the absorbers. For instance, if the absorbers were pancake shapes that were always oriented perpendicular to the line of sight (like face-on spiral galaxies), then we would not cut off the line-of-sight integration at all (\( Z_{\text{cut}} = 0 \), since face-on pancakes at zero separation can still obscure the quasar. For a "hard sphere," we would set \( Z_{\text{cut}} = 2(A/\pi)^{1/2} \), presuming that the obscuring cross section of the absorber drops to zero for points interior to it. As smaller values of \( Z_{\text{cut}} \) will correspond to larger line-of-sight clustering, we henceforth conservatively assume the hard sphere case and use \( Z_{\text{cut}} = 2(A/\pi)^{1/2} \).

Note that one is no longer in the "far-field" limit for the integral in equation (5), and the clustering amplitude \( \chi_\parallel \) explicitly...
depends on the cross section of the absorber. It is easy to understand the nature of this dependence if one considers that the line density \( \propto n A \) is fixed by measurements of \( \langle dN/dz \rangle \). Thus, smaller cross sections correspond to larger volume number densities, but smaller scales near the quasar are being sampled by the integral in equation (5), where the correlation function \( \xi_{QA} \propto r^{-\gamma} \) is large.

 Conversely, larger cross sections sample regions farther from the quasar, and thus \( \xi_{QA} \) is averaged over a larger volume and hence diluted. Figure 2 illustrates the dependence of \( \chi^2(\Delta z) \) on the proper radius of the absorber cross section, \( r_{abs} \equiv (a/h)^{1/2} \), for a range of sizes.

In equations (4) and (5) \( \xi_{QA}(r) \) represents a real space correlation function, and it may appear that we have neglected redshift space distortions. Strictly speaking, the redshift space correlation function \( \xi_{QA}(R, Z) \) should be apparent in equations (4) and (5). This \( \xi_{QA}(R, Z) \) is the convolution of the real space correlation function \( \xi(r) \) with the velocity distribution in the radial direction, which can have contributions from both peculiar velocities and uncertainties in the systemic redshifts of the quasar. However, provided that the distance in redshift space over which we project \( \Delta x \) contains most of the probability under this distribution, it is a good approximation to replace the redshift space correlation function, under the integrals in equations (4) and (5), with the real space correlation function, because peculiar velocities will simply move pairs of points within the volume.

On small spatial scales one should be cognizant of the distinction between absorption “intrinsic” to the host halo of the quasar itself and correlated absorption due to nearby galaxies. The correlation function description presented above is valid in either case; however, intrinsic absorbers may result in excess small-scale clustering relative to the expectation for galaxies. For the transverse clustering measurement, only the closest projected pairs can probe separations small enough to resolve the host galaxy of the quasar, whereas proximate absorbers along the line of sight can probe scales arbitrarily close to the quasar, although peculiar velocities and quasar redshift uncertainties imply that their distance to the quasar cannot be measured. For our projected pair sample, only the closest sight line with \( R = 22 \, h^{-1} \) kpc (proper) is sufficiently small to probe the host of the quasar. A comparison of transverse and line-of-sight clustering is thus complicated by the fact that the line of sight can in principle probe very small scales near the quasar where intrinsic absorption due to the quasar host can play a role.

4. Estimating the Correlation Function

4.1. Maximum Likelihood Estimator

Given a quasar-absorber correlation function \( \xi_{QA} \), equations (2) and (4) describe how to compute the probability of finding an absorber in the redshift interval \( \Delta z = 2(1+z)\Delta v/c \) at a transverse distance \( R \) from a foreground quasar: \( P(R, z) = (dN/dz)\Delta z \). Considering that we only have 17 quasar-absorber pairs selected from 149 sight lines, it will be difficult to measure more than a single parameter with reasonable errors. Hence, we assume the quasar-absorber correlation function to have a power-law form

\[ \xi_{QA} = C(r/r_0)^{-\gamma}, \]

where \( C \) is a clustering amplitude and \( r_0 \) is the correlation length. The amplitude \( C \) is degenerate with \( r_0 \), and we choose to estimate \( C \) because it allows for the possibility of anticorrelation (\( C < 0 \)), which could result from the QSO ionizing radiation field. Motivated by the slope of the LBG autocorrelation function (Adelberger et al. 2005), we choose to fix \( \gamma = 1.6 \). A similar procedure was employed by AS05, who measured clustering of LBGs around luminous quasars (\( 2 \leq z \leq 3.5 \)) and found a best-fit correlation length of \( r_0 = 4.7 \, h^{-1} \) Mpc. We set \( r_0 = 4.7 \, h^{-1} \) Mpc as a fiducial value; thus, \( C \) can be interpreted as the quasar-absorber clustering amplitude relative to the AS05 quasar-LBG result.

Consider an ensemble of \( N \) projected pair sight lines with background quasars at transverse separations \( R_i \) from foreground quasars at redshifts \( z_i \). Given \( \xi_{QA} \), we can compute the associated probabilities \( P_i = P(R_i, z_i) \). Suppose that \( N_{GSLS} \) of these \( N \) sight lines show absorption from super-LLSs with log \( N_{H_i} > 19 \). The likelihood of the data, given the model parameter \( C \), is then

\[ L(C) = \prod_i N_{GSLS}^{-1} \prod_{j \neq i} (1 - P_j), \]

where the probabilities \( P_i \leq 1 \) are capped at 1. By maximizing the likelihood with respect to the parameter \( C \), we estimate the clustering amplitude from the data.

4.2. Monte Carlo Simulations

We must verify that the maximum likelihood estimator in equation (7) is unbiased, and we would also like to know how to assign error bars to an estimate of \( C \). Both of these points can be addressed with Monte Carlo methods. The distribution of redshifts and transverse separations in Figure 1 is not uniform, and it is thus important that we preserve this distribution when constructing mock data sets to assign errors.

For a “true” value of the clustering amplitude \( C \), we can compute the probabilities \( P_i = P(R_i, z_i) \) of observing an absorber for each of the \( N \) projected pair sight lines. Mock data sets can then be constructed by generating an \( N \)-dimensional vector of deviates from the uniform distribution \( x_i \) and assigning sight lines with \( x_i < P_i \) an absorption-line system. The same maximum
likelihood estimator is applied to these mock data sets to determine an estimate $\hat{C}$ for each one, thus allowing us to measure the probability distribution $P(\hat{C}|C)$ of the estimate about the true model.

4.3. Binned Correlation Function

An alternative to the maximum likelihood technique described above would be to estimate the correlation length by fitting a power-law model to estimates of the correlation function in bins of transverse separation. However, because we have only 17 quasar-absorber pairs, the best-fit correlation length from this procedure would be very sensitive to the binning chosen. We compute the correlation function in bins because it provides a useful way to visualize the data, although we do not fit the binned data for $C$.

A simple estimator for the transverse correlation function in equation (2) is

$$\chi_{\perp}(R, \Delta r) = \frac{\langle QA \rangle}{\langle QR \rangle} - 1, \quad (8)$$

where $\langle QA \rangle$ is the number of quasar-absorber pairs in a transverse radial bin centered on $R$, and $\langle QR \rangle = \sum_i \langle dN/dz \rangle \Delta z$ is the number of quasar-random pairs expected. Poisson error bars are used for the binned correlation function. This is reasonable because pairs are spread out over the entire sky; hence, there will be no covariance between the bins, and cosmic variance is also negligible.

4.4. The Column Density Distribution

Before we can estimate the correlation amplitude with equation (7), we require the cosmic average line density of super-LLSs $\langle dN/dz \rangle$. The line density is the zeroth moment of the column density distribution

$$\langle dN/dz \rangle(N_{HI}, z) = \int_{N_{HI}}^{\infty} f_{HI}(N_{HI}, z) dN_{HI}. \quad (9)$$

O'Meara et al. (2007) measured the column density distribution for super-LLSs in the range $19 < \log N_{HI} < 20.3$ at $z \approx 2.7$ and found good agreement with a power law $\langle dN/dz \rangle = A(N_{HI}/10^{19} \text{ cm}^{-2})^b$, where $A = 1.10 \times 10^{-20}$ and $b = -1.43$. For $\log N_{HI} > 20.3$, Prochaska et al. (2005) measured the column density distribution from the SDSS quasar sample in redshift bins.

To evaluate the integral in equation (9), we use the O'Meara et al. (2007) power-law fit in the range $19 < \log N_{HI} < 20.3$ and a spline fit to the Prochaska et al. (2005) results in the redshift bin centered at $z \approx 2.7$. For the redshift evolution, we simply scale the line density of all absorbers by the evolution of DLAs with $\log N_{HI} > 20.3$ measured by Prochaska et al. (2005; see their Figure 8). This procedure assumes that the abundance of super-LLSs evolves similarly to that of DLAs, an assumption that is consistent with but not confirmed by O'Meara et al. (2007).

5. CLUSTERING RESULTS

We applied the maximum likelihood estimator to the 17 quasar-absorber pairs (see Table 1) selected from the 149 projected pair sight lines shown in Figure 1. The maximum likelihood value of the clustering amplitude is $C = 2.9$, which corresponds to a correlation length of $r_0 = 9.2 \text{ h}^{-1} \text{ Mpc}$.

---

6 This is actually an estimator of $\chi_{\perp}(R, \Delta r)$ averaged over the volume of the bin. We ignore this distinction, because the differences are substantially smaller than our errors and we are not fitting parameters from this estimate.

---

In Figure 3 we show the probability distribution of the clustering amplitude maximum likelihood estimates $P(\hat{C})$ for a model with true value equal to our measurement of $C = 2.9$. This distribution was created by applying the maximum likelihood estimator in equation (7) to 100,000 mock realizations of our 149 projected pair sight lines, as described in § 4.2. The mean of this distribution is $\langle \hat{C} \rangle = 2.94$, the dispersion is $\sigma = 0.86$, and the dotted curve shows a Gaussian with the same mean and dispersion. The full distribution (histogram) is used to assign errors to our measurement. [See the electronic edition of the Journal for a color version of this figure.]

---

In Figure 3 we show the probability distribution of the clustering amplitude maximum likelihood estimates $P(\hat{C})$ for a model with true value equal to our measurement of $C = 2.9$. This distribution was created by applying the maximum likelihood estimator in equation (7) to 100,000 mock realizations of our 149 projected pair sight lines, as described in § 4.2. The mean of this distribution is $\langle \hat{C} \rangle = 2.94$, the dispersion is $\sigma = 0.86$, and the dotted curve shows a Gaussian with the same mean and dispersion. The Monte Carlo simulation indicates that our estimator is indeed unbiased and that the error distribution is reasonably well approximated by a Gaussian. Using the full distribution from the Monte Carlo simulation, we compute the 68% confidence interval about the “true” input value, which we use to quote errors on our clustering measurement, $C = 2.9 \pm 0.8$ or $r_0 = 9.2^{+1.3}_{-0.6} \text{ h}^{-1} \text{ Mpc}$. If we assume a steeper slope for the correlation function $\gamma = 2$, we obtain $r_0 = 5.8^{+3.6}_{-0.6} \text{ h}^{-1} \text{ Mpc}$.

We detect strong clustering of super-LLSs around quasars. Figure 4 shows the binned transverse correlation function $\chi_{\perp}$ compared to the two maximum likelihood fits ($\gamma = 1.6$ and $\gamma = 2$) and to the prediction from the quasar-LBG correlation function measured by AS05. For $\gamma = 1.6$, the quasar-absorber clustering amplitude is 3 times larger than the quasar-LBG measurement of AS05 and inconsistent with it at the $\gtrsim 1 \sigma$ level.

The autocorrelation functions of high-redshift galaxies tend to become progressively steeper on (comoving) scales $R \lesssim 1 \text{ h}^{-1} \text{ Mpc}$ characteristic of the sizes of dark matter halos (Coil et al. 2006a; Ouchi et al. 2005; Lee et al. 2006; Conroy et al. 2005); thus, similar behavior might be in cross-correlation around quasars. Indeed, Hennawi et al. (2006a) detected an order of magnitude excess quasar auto-clustering on scales $\lesssim100 \text{ h}^{-1} \text{ kpc}$. For this reason, we also quote our results for $\gamma = 2$, although a steeper slope is not clearly favored by the binned data in Figure 4.

At first glance, it may seem odd that the relative error on our measurement of $r_0$ is $\approx 20\%$ using only 17 quasar-absorber pairs, whereas AS05 quote a $\approx 30\%$ error on $r_0$ from $\approx 200$ quasar-LBG pairs around a sample of $\approx 50$ quasars. The estimator used here is qualitatively similar to that used by AS05 (see also Adelberger...
Fig. 4.—Binned transverse quasar-absorber correlation function for 17 quasar-absorber pairs selected from 149 projected pair sight lines. The lines indicate the best-fit model from our maximum likelihood analysis, and the shaded regions indicate the range allowed by 1σ errors estimated from Monte Carlo simulations. The solid line and the medium gray shaded region are for an assumed correlation function slope of γ = 1.6. The steeper dotted line and dark gray shaded region are for γ = 2.0. The dashed curve and light gray region show the transverse correlation function χv if we set the quasar-absorber correlation function ξzz to the QSO-LBG correlation function measured by AS05 ($r_0 = 4.7 ± 1.3$ h⁻¹ Mpc, $\gamma = 1.6$). [See the electronic edition of the Journal for a color version of this figure.]

e et al. 2005), in that both techniques rely on the radial clustering of pairs of objects at fixed angular positions, because the angular selection functions are unknown (see Adelberger 2005). It is thus worth explaining that our smaller errors arise from a few factors.

First, the relative error decreases with clustering amplitude and our best fit has a factor of 3 larger clustering strength. Second, AS05 exclude scales $R \leq 1.2$ h⁻¹ Mpc from their analysis, whereas four out of our 17 quasar-absorber pairs have $R < 1.2$ h⁻¹ Mpc. Small-scale pairs are effectively “worth” many large-scale pairs because the S/N per pair is much higher. Finally, the AS05 errors are determined from the field-to-field dispersion in the data, which includes a contribution from cosmic variance. Because the projected pairs of quasars are distributed over the entire sky, our measurement does not suffer from cosmic variance errors.

To illustrate that the errors from our Monte Carlo technique are sensible and comparable to the AS05 result, we randomly resampled our pair sight lines with $R > 1.2$ h⁻¹ Mpc to create a mock projected pair sample 30 times larger, but with the same distribution of redshifts and transverse distances. We increased the search window $\Delta v = 3000$ km s⁻¹, in closer agreement with the $l = 30$ h⁻¹ Mpc radial window averaged over by AS05. The average number of quasar-absorber pairs expected from this hypothetical enlarged sample is $\langle N \rangle = \sum P_i = 206$, which is of order the number of LBG-AGN pairs used by AS05. Assuming $\gamma = 1.6$ and $r_0 = 4.7$ h⁻¹ Mpc, our Monte Carlo simulation gives $r_0 = 4.7^{+0.9}_{-1.0}$ h⁻¹ Mpc, or a relative error of ~20%, comparable to the AS05 errors but slightly smaller.

5.1. Systematic Errors
5.1.1. Malmquist Bias

As discussed in § 2, the identification of $\log N_{\rm HI} = 19$ in spectra at the S/N and resolution used in Paper I, can result in a significant Malmquist-type bias because line blending scatters lower column density absorbers upward, and the line density of absorbers $dN/dz$ is a steep function of column density limit. If absorbers with column densities $\log N_{\rm HI} < 19$ scatter up into our sample, this error would bias our clustering measurement high. To investigate the impact of this bias, we redo the clustering analysis but ignore the six quasar-absorber pairs in Table 1 that have column densities within 1σ of the threshold $\log N_{\rm HI} = 19$: SDSS J0256+0039, SDSS J0800+3542, SDSS J0852+2637, SDSS J1152+4517, SDSS J1213+1207, and SDSS J1635+3013. The remaining quasar-absorber pairs give a maximum likelihood clustering amplitude of $C = 1.7 ± 0.7$, or $r_0 = 6.4^{+1.4}_{-1.8}$ h⁻¹ Mpc, compared to our measurement of $C = 2.9 ± 0.8$, or $r_0 = 9.2^{+1.3}_{-1.7}$ h⁻¹ Mpc, for the full sample. This illustrates that even under very conservative assumptions about the possible effect of Malmquist bias, the clustering amplitude would be only reduced by ~1.5σ.

5.1.2. Redshift Errors

Another possible source of bias in our sample could arise from the determination of the foreground quasar redshifts. Note that the clustering analysis properly takes the redshift uncertainties into account by averaging the correlation function over a window of $|\Delta v| = 1500$ km s⁻¹. However, assigning redshifts to the foreground quasar (see § 4 of Paper I) is not a completely objective process. The quasar emission lines sometimes exhibit mild broad absorption line (BAL) or metal line absorption, and the line centering can be sensitive to how these features are masked. It is possible that we were biased toward including quasar-absorber pairs in our sample, and thus tended to assign redshifts resulting in velocity differences $|\Delta v| < 1500$ km s⁻¹. To address this issue, we redo the analysis discarding the three quasar-absorber pairs in Table 1 that have velocity differences larger than the quoted error, $|\Delta v| > |\Delta v|$: SDSS J0225−0739, SDSS J1426+5002, and SDSS J1635+3013. The 14 remaining quasar-absorber pairs give a maximum likelihood clustering amplitude of $C = 2.4^{+0.8}_{-0.7}$, or $r_0 = 8.1^{+1.6}_{-1.4}$ h⁻¹ Mpc. Furthermore, if we discard the five quasar-absorber pairs with the largest velocity differences, we measure $C = 1.9 ± 0.7$, or $r_0 = 7.1^{+1.8}_{-1.7}$ h⁻¹ Mpc.

Another possible source of concern is that for quasars with large redshift errors $\Delta v \gtrsim 1000$ km s⁻¹, the effective volume that we searched for LLSs would be larger than the $|\Delta v| < 1500$ km s⁻¹ that we quote. The actual volume searched would be the result of the convolution of a top-hat distribution of width $|\Delta v| < 1500$ km s⁻¹ with a Gaussian with dispersion set by the redshift error $\Delta v_{\rm fg}$. For the largest errors quoted in Table 1, $\Delta v_{\rm fg} = 1500$ km s⁻¹, this would correspond to a volume about 33% larger, or an effective search window of $|\Delta v| < 2000$ km s⁻¹. To determine the degree to which this biases our results, we re-estimated the correlation function assuming a search window of $|\Delta v| < 2000$ km s⁻¹ and measured $C = 2.5 ± 0.8$, or $r_0 = 8.4^{+1.7}_{-0.9}$ h⁻¹ Mpc. Note that this test is clearly very conservative, since only 6 of our 17 pairs have $\Delta v_{\rm fg}$ as large as 1500 km s⁻¹. For a more typical smaller error of $\Delta v_{\rm fg} = 1000$ km s⁻¹, for the foreground quasars we obtain $C = 2.8$ and $r_0 = 9.0$, or a 0.1σ difference in the clustering strength.

Naively one might have expected the clustering amplitude $C$ to change proportionally with the search volume, but in fact our results are much less sensitive to the exact value of $\Delta v$ used. This is because the probability of having an absorber $P = (dN/dz)[1 + \chi_L(R, \Delta v)] \Delta v$ ($\Delta v = 2(1+z)\Delta v/\cos i$) depends on $\Delta v$ directly (through $\Delta v$), but there is an additional dependence from $\chi_L(R, \Delta v)$. The transverse correlation function $\chi_L$ decreases with increasing $\Delta v$, which counters the direct increase in $P$ from $\Delta v$, and thus our likelihood analysis is very insensitive to the effective search volume.

In conclusion, we find that the larger effective volume caused by quasar redshift errors, or the inclusion of several quasar-absorber
pairs with the velocity differences $|\Delta v| > 1500$ km s$^{-1}$, would only reduce our measured clustering amplitude by $\sim 1 \sigma$.

6. ANISOTROPIC CLUSTERING OF ABSORBERS AROUND QUASARS

If the clustering pattern of optically thick absorbers around quasars is isotropic, then we can use our estimate of the quasar-absorber correlation function in $\S$ 5 to predict the number of “proximate” super-LLSs that should be observed in a given velocity window, $\Delta v$, along the line of sight. According to equation (5), the clustering enhancement $\xi_{||}$ can be computed by averaging $\xi_{\parallel A}$ over a cylinder of length $\Delta v/aH(z)$ and cross sectional area $A$.

However, because the cross section of the absorbers is unknown, relating the transverse clustering to the line-of-sight clustering requires an assumption about the size of the cross section. Very little is known about the sizes of DLAs and LLSs. Briggs et al. (1989) detected H i 21 cm absorption of a DLA with $N_{\text{HI}} = 5 \times 10^{21}$ cm$^{-2}$ against an extended radio source, allowing them to place a lower limit of $r \geq 12 h^{-1}$ kpc on the size of the absorbing region. Prochaska (1999) estimated an absorbing path length of $\sim 2 h^{-1}$ kpc for a super-LLS with $N_{\text{HI}} = 19.1$ by comparing the column density to the total volume density, which was determined from the collisionally excited C $\equiv$ $\lambda$1335 transition. Adelberger et al. (2006) constrained the size of a DLA with $N_{\text{HI}} = 20.4$ to be $\geq 8 h^{-1}$ kpc, based on their detection of fluorescent Ly$\alpha$ emission from the edge of a DLA galaxy situated $\sim 8 h^{-1}$ kpc from the location of DLA absorption. Lopez et al. (2005) measured identical column densities of $N_{\text{HI}} = 10^{20.5}$ cm$^{-2}$ for both DLAs at $z = 0.9313$ detected in the individual images of the gravitational lens HE 0512$-$3329, allowing them to constrain the size of the DLA to be $\geq 4 h^{-1}$ kpc (see also Smette et al. 1995). It is not clear how to relate these measurements to the absorption cross sections of the log $N_{\text{HI}} > 19$ of interest to us here.

To determine the cross section size as a function of limiting column, $r_{\text{abs}}(>N_{\text{HI}}) \equiv [aA(>N_{\text{HI}})/n]^{1/2}$, we adopt the simple approximation that the comoving number density of absorption-line systems, $n$, and the covering factor, $f_{\text{cov}}$, are independent of column density, which gives the simple scaling $r_{\text{abs}} \propto (\langle dN/dz \rangle)^{1/2}$ from equation (1). Two families of sizes, “small” and “large” are considered, which we believe bracket the range of possibilities. Fiducial physical sizes of $r_{\text{abs}} = 5$ and $20 h^{-1}$ kpc are chosen at the DLA threshold ($log N_{\text{HI}} > 20.3$) for the small and large absorbers, respectively. The $r_{\text{abs}} \propto (\langle dN/dz \rangle)^{1/2}$ scaling then predicts respective sizes of $r_{\text{abs}} = 9$ and $38 h^{-1}$ kpc for super-LLS with $log N_{\text{HI}} > 19$.

In Figure 5 we show the probability that a quasar at $z = 2.5$ will have a “proximate” optically thick absorption-line systems within $\Delta v < 3000$ km s$^{-1}$, as a function of limiting column density. The left (right) panel shows the prediction for the small (large) family of cross section sizes, and the dot-dashed curves shows the prediction in the absence of clustering ($\xi_{||} = 0$), which is simply the integral of the column density distribution in equation (9). Since we have measured the transverse clustering only for log $N_{\text{HI}} > 19$, this figure assumes that clustering is independent of limiting column density.

The transverse clustering overpredicts the fraction of quasars that have a proximate absorber by a large factor. For example, for small absorption cross sections and $\gamma = 1.6$, the quasar-absorber correlation function measured from the transverse direction predicts that a fraction $P = 0.30 \pm 0.07$ of all quasars should show a proximate super-LLS ($log N_{\text{HI}} > 19$) within $\Delta v = 3000$ km s$^{-1}$. Even the AS05 clustering amplitude, which is a factor of $\sim 3$ smaller than our best fit, would predict $P = 0.12^{+0.08}_{-0.06}$. A steeper correlation function results in even more proximate absorbers. For the best-fit transverse clustering amplitude with $\gamma = 2$, the probability would be $P = 0.49^{+0.17}_{-0.10}$.

Making the absorbers larger changes this prediction by factors of $\sim 2$. The large absorbers predict that a fraction $P = 0.14 \pm 0.03$ of quasars should have a proximate absorber, given our best-fit clustering amplitude for $\gamma = 1.6$. Our steeper $\gamma = 2$ fit gives $P = 0.14^{+0.04}_{-0.02}$, and the AS05 result predicts $P = 0.07 \pm 0.03$. Although the line density of proximate super-LLSs near quasar has yet to be measured, it is incontrovertible that 15% of quasars do not show a super-LLS within $\Delta v < 3000$ km s$^{-1}$ along the line of sight.

J. X. Prochaska et al. (2007, in preparation) recently measured the line density of proximate DLAs ($log N_{\text{HI}} > 20.3$) with $\Delta v < 3000$ km s$^{-1}$ from a sample of $\sim 100$ of these systems selected...
from ~6000 quasars from the SDSS DR5. They found that the number of proximate DLAs was enhanced by a factor of 1.4 ± 0.1 over the expectation from the statistics of intervening absorbers (Prochaska et al. 2005), over the redshift range 2.2 ≤ z ≤ 4. At lower redshifts z ~ 2.5, characteristic of the mean of our projected pair sample, they found ~10 proximate DLAs out of ~2000 SDSS quasars with z < 2.7, corresponding to an overdensity of 1.2 ± 0.15 over the expectation from the cosmic average. The point with the error bar in Figure 5 indicates the probability of having a proximate DLA from the J. X. Prochaska et al. (2007, in preparation) measurement, P_{DLA} = 0.0095 ± 0.001. Our best-fit clustering amplitude predicts that P = 0.12 ± 0.3 (P = 0.25^{+0.09}_{-0.05}) of quasars should have a nearby DLA for small absorbers and γ = 1.6 (γ = 2). Large absorbers change this prediction to P = 0.055 ± 0.013 (P = 0.069^{+0.23}_{-0.01}).

The caveat should be included that our prediction for the number of proximate absorbers from the transverse clustering is very sensitive to the small-scale behavior of the correlation function. Specifically, using equation (5) to predict the line-of-sight clustering implicitly assumes that the power-law model of the correlation function, ξ ∝ r^{-γ}, is valid down the lower limit of the integration, Z_{cut}, which we have set to be the diameter of the absorbers. For super-LLSs, we used (proper) radii of r_{abs} = 9 and 38 h^{-1} kpc, for small and large absorbers, respectively, corresponding to (comoving) Z_{cut} = 63 and 266 at z = 2.5. The smallest transverse separation of our projected pair sample is R = 72 h^{-1} kpc, and there are just five sight lines with R ≤ 300 h^{-1} kpc, three of which have an absorber (see Fig. 1 and Table 1). The transverse measurement assumes a single power law from R = 70 h^{-1} kpc to 5 h^{-1} Mpc. One should bear in mind that only a handful of projected pairs probe the small scales (R ≤ 300 h^{-1} kpc) that the line-of-sight clustering is very sensitive to, but it is reassuring that closest bin in Figure 4 is consistent with the power-law fit.

We have shown that the transverse clustering that we quantified in § 5 overpredicts the abundance of proximate absorbers along the line of sight by a large factor, ~4−20, under reasonable assumptions about the sizes of the cross sections of these absorbers. The clustering pattern of absorbers around quasars is thus highly anisotropic. The most plausible explanation for this anisotropy is that the transverse direction is less likely to be illuminated by ionizing photons than the line of sight and that the optically thick absorbers along the line of sight are being photoevaporated. We discuss the physical effects that could give rise to this anisotropy in § 8. Next, we introduce a simple model that provides physical insight into the problem of optically thick absorbers subject to the intense ionizing flux of a nearby quasar.

### 7. Photoevaporation of Optically Thick Clouds

The problem of an optically thick absorption-line system exposed to the ionizing flux of a nearby luminous quasar is analogous to that of a neutral interstellar cloud being exposed to the ionizing radiation of an OB star, a problem that was first investigated by Oort & Spitzer (1955). Bertoldi (1989) classified the behavior of photoevaporating clouds based on their initial column density and the ionization parameter at the location of the cloud, and he developed an analytical solution to follow the radiation-driven implosion phase of the cloud. Interestingly, although Bertoldi (1989) was primarily concerned with the fate of interstellar clouds near OB stars in H II regions, he commented briefly on the applicability of the same formalism to Lyα clouds exposed to the ionizing flux of a quasar.

#### 7.1. Cloud Zapping

Following Bertoldi (1989), we model an optically thick absorber as a homogeneous spherical neutral gas cloud with total number density of hydrogen n_{H} that is embedded in photoionized intergalactic medium at temperature T = 20,000 K, corresponding to an isothermal sound speed c_{s} = 16.57^{1/2}_0 km s^{-1}, where T_{20} is the temperature in units of 20,000 K. If the cloud is at a distance r from a luminous quasar that is emitting S ionizing photons per second, then the ionizing flux at the cloud surface, F_{i} = S/4πr^{2}, will drive an ionization front into the neutral gas. If the flux is large enough to make the conditions R-type (see Spitzer 1978 for a discussion of how ionization fronts are classified), an R-type ionization front will propagate through the cloud without dynamically perturbing the neutral gas. As the front propagates into the cloud, it ionizes an increasing column of neutral gas, steadily reducing the ionizing flux at the front, until the conditions become M-type, at which point the front will stall and drive a shock into the neutral upstream gas. This shock will impede the cloud and compress it until conditions become D-type, allowing the front to continue propagating and establishing a steady photoevaporation flow (Bertoldi 1989).

The cloud will be “zapped,” or completely photoevaporated, if the ionizing flux is large enough relative to the column density such that the entire cloud can be ionized in a recombination time. In this case, the R-type front will completely cross the cloud without stalling. Part of the cloud will remain neutral and a shock will form provided that

\[ \delta = 494N_{H,20.3}^{-1} \left[ \Gamma - 1.1 \times 10^{-4}T_{20}^{1/2} \right] < 1, \]

where \( N_{H,20.3} \) is the total hydrogen column in units of \( 10^{20.3} \) cm^{-2}, and the ionization parameter is defined by \( \Gamma \equiv F_{i}/n_{H}c_{s} \), with

\[ \Gamma = 2.58 \times 10^{-5} S_{56} r_{Mpc}^{-2} n_{H,1}^{-1}, \]

where \( S_{56} \) is the ionizing flux in units of \( 10^{56} \) s^{-1}, \( r_{Mpc} \) is the physical distance in units of Mpc, and \( n_{H,1} \) is the total hydrogen number density in units of \( 1 \) cm^{-3}. The condition that the ionization front be R-type at the surface of the cloud is \( \Gamma > 1.1 \times 10^{-4}T_{20}^{1/2} \).

Consider our fiducial example of a foreground quasar with \( r = 19 \) at an angular separation of \( \Delta \theta = 1^{\prime} \) from an absorber, corresponding to a transverse proper distance of 485 kpc. The ionizing flux is enhanced by \( g_{UV} = 130 \) over the UV background and \( S_{56} = 5.2 \). For a DLA with total hydrogen column of \( N_{H} = 10^{20.3} \) cm^{-2} at this distance, the cloud will survive (\( \delta < 1 \)) provided \( n_{H} > 0.27 \) cm^{-3}, which would give \( \Gamma < 0.002 \).

The left panel of Figure 6 shows the lower limits on the volume density of a DLA with neutral hydrogen column \( \log N_{H} = 20.3 \), set by the condition for cloud survival, as a function of physical distance from a quasar at \( z = 2.5 \). The dashed, solid, and dotted curves correspond to \( r = 17, 19, \) and 21 mag, respectively. In the region below each curve, the volume densities are too small and the clouds are photoevaporated, whereas above the curves the clouds can survive. The right panel shows the lower limit on the neutral hydrogen column density as a function of distance, assuming a volume density \( n_{H} = 0.1 \). If DLAs with \( \log N_{H} = 20.3 \) have sizes in the range \( r_{abs} \sim 1-5 \) kpc their corresponding number densities are \( n_{H} \sim N_{H}/r_{abs} \approx 0.01-1 \). Thus according to Figure 6 optically thick absorbers with \( n_{H} \lesssim 0.1 \) will be photoevaporated if they lie within \( \sim 1 \) Mpc of a luminous quasar.

Note that the condition in equation (6) considers the total column density \( N_{H} \), not the neutral column, \( N_{H} \). Although DLAs are expected to be predominantly neutral \( N_{H} \), the...
ionic absorption lines typically observed in LLSs suggest that they are the photoionized analogs of DLAs (Prochaska 1999) and that their ionization state is determined by ionization equilibrium with the UV background. In equation (10), we have assumed that optically thick absorbers are spherical top-hat density distributions. Hence, an LLS with column density $N_{HI} \leq 20$ can be thought of as a sight line that passes through the photoionized outskirts of a top-hat cloud that has a larger total hydrogen column $N_H$, and the total column determines the ability of the cloud to survive a blast of ionizing radiation from the quasar. Thus for $N_{HI} \leq 20$, we compute an ionization correction with the standard approach, which is to assume a slab geometry and determine the ionization balance in a uniform background, using a photoionization code such as Cloudy (Ferland et al. 1998). To construct the curve in the right panel of Figure 6, we interpolated through a grid of Cloudy solutions for $N_{HI}(N_H)$.

7.2. A Toy Model to Predict the Statistics of Proximate DLAs

In this section we use a toy model to illustrate how quasar-absorber clustering can be used to constrain the physical properties of optically thick absorbers. The criterion $\delta < 1$ in equation (10) gives a minimum distance from the quasar $R_{SS}(n_{HI})$, as a function of volume density, at which an optically thick absorption-line system with column density $N_{HI}$ can survive. Our approach is to simply assume that absorbers at smaller distances are photoevaporated and absorbers at larger distances survive. We also assume that the transverse direction is not illuminated by the quasar, and hence the transverse clustering measures the intrinsic quasar-absorber clustering, in the absence of ionization effects. Because proximate absorbers are definitely illuminated, this intrinsic clustering is then reduced along the line of sight by photoevaporation.

For the column density range $\log N_{HI} > 20.3$, we evaluate $R_{SS}$ at the lower limit $\log N_{HI} = 20.3$, which is a decent approximation because the column density distribution is steep and the statistics will be dominated by absorbers near the threshold. To simplify the computation, we take $R_{SS}$ to be a distance only along the line of sight, which is valid provided that $R_{SS} \gg A^{1/2}$. Then we can write that the line density of absorbers within $\Delta v < 3000$ km s$^{-1}$ is

$$dN = \langle dN \rangle \left[ 1 - \frac{aR_{SS}H(z)}{\Delta v} + \chi_{||}(\Delta v) \right], \quad (12)$$

where $\chi_{||}$ is given by equation (5) but with $Z_{cut} = R_{SS}$. The assumption that the transverse direction gives the intrinsic clustering in the absence of ionization effects amounts to using the correlation function $\xi_{QA}$, measured from the transverse clustering, in the line-of-sight integral in equation (5).

In Figure 7 we show our toy model prediction for the probability of a quasar having a proximate DLA with $\log N_{HI} > 20.3$ within $\Delta v < 3000$ km s$^{-1}$ as a function of total volume density of hydrogen $n_H$. We assumed that the DLAs have a size of $r_{abs} = 5$ h$^{-1}$ kpc, characteristic of the small absorbers discussed in § 6. However, identical results are obtained for large absorbers ($r_{abs} = 20$ h$^{-1}$ kpc). Because our toy model excludes small scales $r_{abs} < R_{SS}$ from the clustering integral in equation (5), we are again in the far-field limit where the volume average is nearly independent of the absorber cross section. This independence breaks down for very large densities $n_H \gtrsim 10^3$, where $R_{SS}$ approaches the size of the absorbers (see Fig. 7). The curves and shaded regions show the predictions and $1\sigma$ errors for the transverse clustering measured in § 5, as well as the clustering strength measured by AS05. We assumed a quasar with magnitude $r = 19.1$ at $z = 2.5$, chosen to match the mean magnitude and redshift of the proximate DLA sample of J. X. Prochaska et al. (2007, in preparation). The long-dashed horizontal lines indicate the measurement and $\pm 1\sigma$ range measured by J. X. Prochaska et al. (2007, in preparation) of $P_{DLA} = 0.0095 \pm 0.001$.

Our toy model suggests that DLAs with volume densities in the range $10^{-3}$ cm$^{-3} \leq n_H \leq 10^{-1}$ cm$^{-3}$ are required to agree with the measurement of J. X. Prochaska et al. (2007, in preparation). Even the weaker AS05 clustering of LBGs around quasars would require $n_H \leq 1$ cm$^{-3}$. For larger volume densities, DLAs illuminated by quasars would survive at smaller radii where the clustering is strong, giving rise to a larger number of proximate DLAs. Note that the comparison of our toy model to the J. X. Prochaska et al. (2007, in preparation) measurement in Figure 7 assumes that the clustering of absorbers is independent of column
density threshold (i.e., our measurement is for log $N_{HI} > 19$). This assumption was made because our quasar-absorber sample did not have sufficient statistics to measure the quasar-absorber clustering for DLAs alone (see § 5).

Although crude, this model illustrates how a comparison of line-of-sight and transverse quasar absorber clustering can be used to determine the density distribution in optically thick absorbers. Detailed models of self-shielding with radiative transfer (Zheng & Miralda-Escudé 2002a; Cantalupo et al. 2005; J. A. Kollmeier et al. 2007, in preparation) would be required for a more accurate treatment, and such analyses could easily include cuspy density profiles or a multiphase distribution of gas. Although better statistics and more theoretical work are necessary, the clustering of optically thick absorbers around quasars will provide important new constraints on the physical nature of these systems.

8. SUMMARY AND DISCUSSION

8.1. Summary

In this paper we used a sample of 17 super-LLSs (log $N_{HI} < 19$) selected from 149 projected quasar pairs sight lines in Paper I to investigate the clustering pattern of optically thick absorbers around quasars. Based on these data, we find the following results:

1. A simple formalism is presented for quantifying the clustering of absorbers around quasars in both the transverse and line-of-sight directions. The clustering of absorbers around quasars in the transverse direction is independent of the size of the absorption cross section, whereas the line-of-sight clustering was shown to be sensitive to the cross section size.

2. Applying this formalism to the 17 super-LLSs (log $N_{HI} < 19$) selected from 149 projected quasar pair sight lines with mean redshift $z = 2.5$, we determine a comoving correlation length of $r_0 = 9.2^{+1.3}_{-0.8}$ Mpc for a power-law correlation function with $\gamma = 1.6$. This is 3 times stronger than the clustering of LBGs around quasars recently measured by AS05. If we assume a steeper slope of $\gamma = 2.0$, we measure $r_0 = 5.8^{+1.0}_{-0.6}$ Mpc.

3. The clustering of optically thick absorbers around quasars is highly anisotropic. If we apply the clustering amplitude measured in the transverse direction to the line of sight, the fraction of quasars that have a proximate absorber within $\Delta v < 3000$ km s$^{-1}$ is overpredicted by a factor as large as $4-20$, depending on assumptions about cross section sizes and the slope of the correlation function. The most plausible explanation for the anisotropy is that the transverse direction is less likely to be illuminated by ionizing photons than the line of sight and that the optically thick absorbers along the line of sight are being photoevaporated.

4. A simple model of absorbers as uniform spherical overdensities is discussed and we give an analytic criterion that determines whether an absorber illuminated by a quasar will be able to self-shield. This criterion indicates that optically thick absorbers with $N_{HI} \lesssim 0.1$ will be photoevaporated if they lie within $\sim 1$ Mpc of a luminous quasar. We combine this criterion with a toy model of the effect of photoevaporation on line-of-sight clustering to illustrate how comparisons of the line-of-sight and transverse clustering around quasars can ultimately be used to constrain the distribution of gas in optically thick absorption-line systems. A similar experiment applied to Mg II, C IV, or other metal absorption-line systems near quasars (Bowen et al. 2006; G. E. Prochter et al. 2007, in preparation) would also yield valuable insights into their physical nature.

8.2. Discussion

The anisotropic clustering pattern of absorbers around quasars suggests that the transverse direction is less likely to be illuminated by ionizing photons than the line of sight. This suggestion gains credulity in light of the null detections of the transverse proximity effect in the Ly$\alpha$ forests of projected quasar pairs (Crotts 1989; Dobrzycki & Bechtold 1991; Fernandez-Soto et al. 1995; Liske & Williger 2001; Schirber et al. 2004; Croft 2004; but see also Jakobsen et al. 2003). Although these studies are each based only on a handful of projected pairs, they all come to similar conclusions: the amount of (optically thin) Ly$\alpha$ forest absorption in the background quasar sight line near the redshift of the foreground quasar is larger than average rather than smaller, the opposite of what is expected from the transverse proximity effect. Two physical effects can explain both the optically thin results and our result for optically thick systems: anisotropic emission or variability, which we discuss in turn.

If quasar emission is highly anisotropic, the line of sight would be exposed to the ionizing flux of the quasar, whereas transverse absorbers would be more likely to lie in shadowed regions. Studies of Type II quasars and the X-ray background suggest that quasars with luminosities comparable to our foreground quasar sample ($M_B \lesssim -23$) have $\sim 30\%$ of the solid angle obscured (Ueda et al. 2003; Barger et al. 2005; Treister & Urry 2005), although these estimates are highly uncertain. Naively, we would expect the covering factor of transverse absorbers to be approximately equal to the average fraction of the solid angle obscured. But in Paper I we found a very high covering factor (6/8) for having an optically thick absorber with log $N_{HI} > 17.2$ (see Fig. 1 of Paper I) on the smallest (proper) scales $R < 150$ h$^{-1}$ kpc. Although the statistics are clearly very poor, this high covering factor is suggestive of a significantly larger obscured fraction.

If the ionizing flux of the foreground quasar varies considerably on a timescale shorter than the transverse light crossing time...
between the foreground and background sight lines, a transverse proximity effect might not be observable. This is because the ionization state of the gas along the transverse sight lines is sensitive to the foreground quasars luminosity a light crossing time before the light that we observe was emitted. At 60 quasars luminosity a light crossing time is 1.1 × 10^6 yr.

Currently, the lower limit on the intermittency of quasar emission comes from observations of the (optically thin) proximity effect (Bajtlik et al. 1988; Scott et al. 2000) in the Ly forest nearly quasars. The presence of an optically thin proximity effect implies that the IGM has had time to reach ionization equilibrium with the quasars increased ionizing flux, which requires that the duration of a burst of quasar radiation is longer than the IGM equilibration time, t_{burst} ≈ 10^4 yr (Martini 2004). The photoevaporation timescale for an optically thick absorber is \( \sim N_{HI}/F \) or the light crossing time, whichever is longer, where \( F \) is the ionizing flux. At a distance of 100 kpc from an i = 19 quasar, it would take 2.5 quasar the transverse light crossing time is 1.1 × 10^6 yr.

Using the ionizing flux of a quasar to study the distribution of neutral gas in optically thick absorbers is a powerful new way to study these absorption-line systems. We have shown how comparisons of the line-of-sight and transverse clustering of absorbers around quasars constrains their distribution of gas. Theoretical models of LLs and DLA that include radiative transfer and self-shielding (Zheng & Miralda-Escudé 2002a; Cantalupo et al. 2005; J. A. Kollmeier et al. 2007, in preparation) should explain how morphology, cuspy density profiles, or a multiphase medium change the ability of absorbers to survive near quasars.
Large samples of optically thick absorption-line systems near quasars are well within reach, for transverse systems using quasar pairs as well as proximate absorbers along the line of sight. This data will provide new opportunities to characterize the environments of quasars and the physical nature of absorption-line systems, and it will uncover new laboratories for studying fluorescence emission from optically thick absorbers.

We are grateful to Jordi Miralda-Escudé, Juna Kollmeier, Piero Madau, and Zheng Zheng for reading an early version of this manuscript and providing critical comments. We thank John O’Meara, Yue Shen, and Michael Strauss for sharing results prior to publication and for helpful discussions. J. F. H. acknowledges enlightening discussions with Kurt Adelberger, Doron Chelouche, Bruce Draine, Sara Ellison, Taotao Fang, Gabe Prochter, Chris McKeel, Brice Menard, David Russell, Alice Shapley, and Michael Strauss. J. F. H. is supported by NASA through Hubble Fellowship grant 01172.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555. J. X. P. wishes to acknowledge funding through NSF grant AST-0307408. The conclusions of this work are based on data collected from observatories at the summit of Mauna Kea. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

REFERENCES

Adelberger, K. L. 2005, ApJ, 621, 574
Adelberger, K. L., & Steidel, C. C. 2005, ApJ, 630, 50 (AS05)
Adelberger, K. L., Steidel, C. C., Kollmeier, J. A., & Reddy, N. A. 2006, ApJ, 637, 74
Adelberger, K. L., Steidel, C. C., Pettini, M., Shapley, A. E., Reddy, N. A., & Erb, D. K. 2005, ApJ, 619, 697
Adelberger, K. L., Steidel, C. C., Shapley, A. E., & Pettini, M. 2003, ApJ, 584, 45
Bahcall, J. N., Schmidt, M., & Gunn, J. E. 1969, ApJ, 157, L77
Bahcall, N. A., & Chokshi, A. 1991, ApJ, 380, L9
Baglioni, S., Duncan, R. C., & Ostriker, J. P. 1988, ApJ, 327, 570
Barger, A. J., Cowie, L. L., Mushotzky, R. F., Yang, Y., Wang, W.-H., Steffen, A. T., & Capak, P. 2005, AJ, 129, 758
Bertoldi, F. 1989, ApJ, 346, 735
Boué, N., & Lowenthal, J. D. 2004, ApJ, 609, 513
Bowen, D. V., et al. 2006, ApJ, 645, L105
Briggs, F. H., Wolfe, A. M., Liszt, H. S., Davis, M. M., & Turner, K. L. 1989, ApJ, 341, 650
Brown, M. J. I., Boyle, B. J., & Webster, R. L. 2001, AJ, 122, 26
Cantalupo, S., Porciani, C., Lilly, S. J., & Miniati, F. 2005, ApJ, 626, 767
Cooke, J., Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2003, ApJ, 666, 1042
Crotts, A. P. S. 1989, ApJ, 336, 550
Dobrzycki, A., & Bechtold, J. 1991, ApJ, 377, L69
Efstathiou, G., Frenk, C. S., White, S. D. M., & Davis, M. 1988, MNRAS, 235, 715
Ellison, S. L., Yan, L., Hook, I. M., Pettini, M., Wall, J. V., & Shaver, P. 2002, A&A, 383, 91
Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, PASP, 110, 761
Fernandez-Soto, A., Barcons, X., Carballo, R., & Webb, J. K. 1995, MNRAS, 277, 235
Gawiser, E., Wolfe, A. M., Prochaska, J. X., Lanzetta, K. M., Yahata, N., & Quirrenbach, A. 2001, ApJ, 562, 628
Gould, A., & Weinberg, D. H. 1996, ApJ, 468, 462
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Hennawi, J. F., et al. 2006a, AJ, 131, 1
Hennawi, J. F., et al. 2006b, ApJ, 651, 61 (Paper I)
Jakobsen, P., Jansen, R. A., Wagner, S., & Reimers, D. 2003, A&A, 397, 891
Lee, K.-S., Giavalisco, M., Gnedin, O. Y., Somerville, R. S., Ferguson, H. C., Dickinson, M., & Ouchi, M. 2006, ApJ, 642, 63
Liske, J., & Williger, G. M. 2001, MNRAS, 328, 653
Lopez, S., Reimers, D., Gregg, M. D., Wisotzki, L., Wucknitz, O., & Guzman, A. 2006, ApJ, 626, 767
Martini, P. 2004, in Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), 169
Meiksin, A. 2005, MNRAS, 356, 596
Miralda-Escudé, J. 2003, ApJ, 597, 66
Mo, H. J., & White, S. D. M. 1996, MNRAS, 282, 347
Möller, P., Warren, S. J., Fall, S. M., Fynbo, J. U., & Jakobsen, P. 2002, ApJ, 574, 51
Möller, P., Warren, S. J., & Fynbo, J. U. 1998, A&A, 330, 19
O’Meara, J. M., et al. 2007, ApJ, in press (astro-ph/0610726)
Oort, J. H., & Spitler, L. J. 1955, ApJ, 121, 6
Ouchi, M., et al. 2005, ApJ, 635, L117
Péroux, C., Dessauges-Zavadsky, M., D’Odorico, S., Sun Kim, T., & McMahon, R. G. 2005, MNRAS, 363, 479
Péroux, C., McMahon, R. G., Storrie-Lombardi, L. J., & Irwin, M. J. 2003, MNRAS, 346, 1103
Porciani, C., Magliocchetti, M., & Norberg, P. 2004, MNRAS, 355, 1010
Prochaska, J. X. 1999, ApJ, 511, L71
Prochaska, J. X., Herbert-Fort, S., & Wolfe, A. M. 2005, ApJ, 635, 123
Richards, G. T., Vanden Berk, D. E., Reichard, T. A., Hall, P. B., Schneider, D. P., SubbaRao, M., Thakar, A. R., & York, D. G. 2002, AJ, 124, 1
Russell, D. M., Ellison, S. L., & Benn, C. R. 2006, MNRAS, 367, 412
Schaye, J. 2001, ApJ, 559, 507
Schirber, M., Miralda-Escudé, J., & McDonald, P. 2004, ApJ, 610, 105
Scott, J., Bechtold, J., Dobrzycki, A., & Kulkarni, V. P. 2000, ApJ, 130, 617
Serber, W., Bechtold, N., Menard, B., & Richards, G. 2006, ApJ, 643, 68
Shapley, A. E., et al. 2006b, ApJ, 651, 688
Shen, Y., et al. 2007, AJ, submitted
Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 119
Smette, A., Robertson, J. G., Shaver, P. A., Reimers, D., Wisotzki, L., & Koehler, T. 1995, A&AS, 113, 199
Smith, R. J., Boyle, B. J., & Maddox, S. J. 2000, MNRAS, 313, 252
Spergel, D. N., et al. 2003, ApJS, 148, 175
Spitzer, L. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)
Treister, E., & Urry, C. M. 2005, ApJ, 630, 115
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886
Yee, H. K. C., & Green, R. F. 1984, ApJ, 280, 79
———. 1987, ApJ, 319, 28
Zheng, Z., & Miralda-Escudé, J. 2002a, ApJ, 568, L71
———. 2002b, ApJ, 578, 33