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PROBING THE IGM-GALAXY CONNECTION TOWARD PKS0405−123 II : A CROSS-CORRELATION STUDY OF Lyα ABSORBERS AND GALAXIES AT $Z < 0.5$[1]

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ABSTRACT

We present a pilot study of the clustering properties of Lyα absorbers with respect to known galaxies based on 112 Lyα absorbers and 482 galaxies identified at $z < 0.5$ along the sightline toward PKS0405−123. The principal goal is to determine the origin of Lyα absorbers based on their cross-correlation amplitude with known galaxies and investigate a possible N(H I) dependence of the cross-correlation function. The main results of our study are as follows. (1) The cross-correlation function ξ_{ga} measured using only emission-line dominated galaxies and Lyα absorbers of log N(H I) ≥ 14 shows a comparable strength to the galaxy auto-correlation function ξ_{gg} on co-moving, projection distance scales $< 1\,h^{-1}$ Mpc, while there remains a lack of cross-correlation signal when using only absorption-line dominated galaxies. This signifies a morphology-dependent ξ_{ga} and indicates that strong absorbers of log N(H I) ≥ 14 and emission-line galaxies reside in the same halo population. (2) A maximum-likelihood analysis shows that Lyα absorbers of log N(H I) < 13.6 are consistent with being more randomly distributed with respect to known galaxies. Finally, (3) we find based on this single sightline that the amplitude of ξ_{ga} does not depend sensitively on N(H I) for strong absorbers of log N(H I) ≥ 13.6.

Subject headings: galaxies: evolution—quasars: absorption lines

1. INTRODUCTION

The forest of Lyα absorption line systems observed in the spectra of background QSOs offers a sensitive probe of the tenuous, large-scale baryonic structure that is otherwise invisible (e.g. Rauch 1998). Over the last several years, various numerical simulations have predicted that approximately 40% of the total baryons at redshift $z = 0$ reside in diffuse intergalactic gas of temperature $T < 10^5$ K that gives rise to the Lyα absorbers (e.g. Davé et al. 2001). Indeed, Penton, Stocke, & Shull (2002, 2004) argue that Lyα absorbers of neutral hydrogen column density N(H I) $\leq 10^{14.5}$ cm^{-2} may contain between $20 - 30$% of the total baryons in the nearby universe based on observations of the local Lyα forest and a simple assumption of the cloud geometry. Furthermore, their comparison between galaxies and absorbers along common lines of sight implies that roughly 20% of low-redshift Lyα absorbers originate in regions where no luminous galaxies are found within 2 h^{-1} Mpc radius. They conclude that ≈ 5% of all baryons are in voids.

Whether or not Lyα absorbers trace the typical galaxy population bears directly on the efforts to locate the missing baryons in the present-day universe (Persic & Salucci 1992; Fukugita, Hogan, & Peebles 1998), and to apply known statistical properties of the Lyα absorbers for constraining statistical properties of faint galaxies. This issue remains, however, unsettled (Lanzetta et al. 1995; Stocke et al. 1995; Chen et al. 1998, 2001; Penton et al. 2002). While nearly all galaxies within 180 h^{-1} kpc physical radius of the QSO lines of sight have associated Lyα absorbers of N(H I) $\geq 10^{14}$ cm^{-2} that are less than a velocity separation $v = 250$ km s^{-1} away along the sightline (Chen et al. 1998, 2001), not all Lyα absorbers have a galaxy found within 1 h^{-1} Mpc physical distance to a luminosity limit of $0.5\,L_*$ (Morris et al. 1993; Tripp et al. 1998). Despite the discordant interpretations in associating Lyα absorbers with galaxies, the Lyα absorbers (particularly those of N(H I) $\geq 10^{14}$ cm^{-2}) are consistently found to be correlated with known galaxies (Morris et al. 1993; Bowen, Pettini, & Blades 2002) but at a weaker clustering strength than what is measured between field galaxies. The weak cross-correlation amplitude between galaxies and absorbers has led to the conclusion that the Lyα absorbers trace large-scale filamentary structures, rather than individual galactic halos (e.g. Grogin & Geller 1998; Tripp et al. 1998).

However, galaxies are known to be a biased tracer of the underlying dark matter halos and the bias depends on morphology and luminosity (see e.g. Davis & Geller 1976; Loveday et al. 1995; Madgwick et al. 2003). The weaker cross-correlation amplitude observed between galaxies and Lyα absorbers, when compared with galaxy auto-correlation studies, can possibly be explained by a difference in galaxy bias. In this Letter, we present a pilot study of the galaxy–Lyα absorber cross-correlation function based on the Lyα absorbers and galaxies identified along the sightline toward PKS0405−123. The primary objectives of the study are (1) to compare the galaxy–absorber cross-correlation function with galaxy auto-correlation function for galaxies of different properties, and (2) to obtain a quantitative

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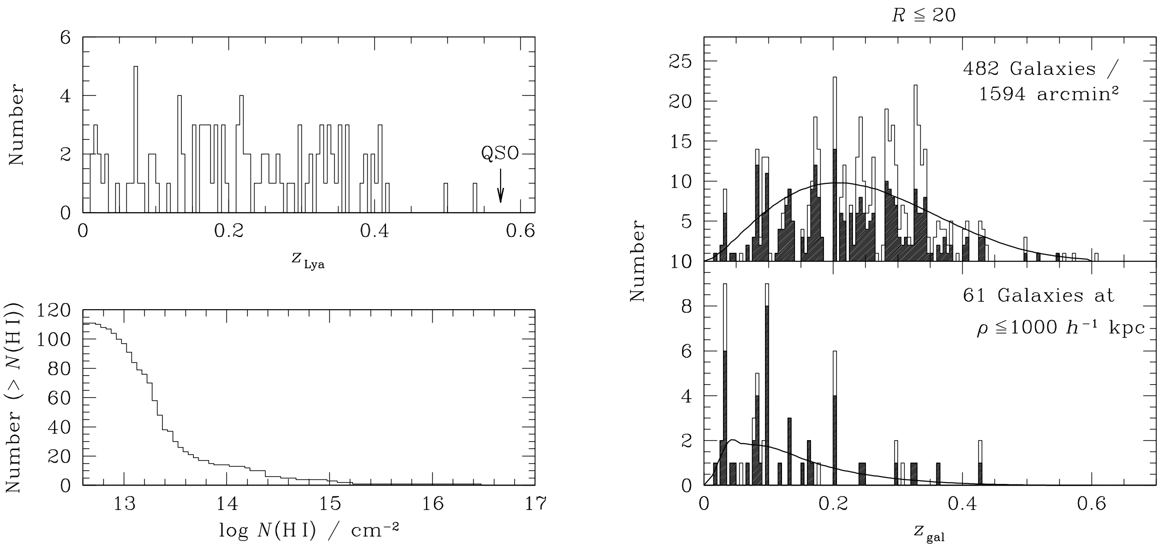

FIG. 1.— Left: The top panel shows the redshift distribution of all 112 Lyα absorbers identified along the sightline toward PKS0405−123. The detection limit of Lyα absorption lines is uniform at $N(\text{H I}) = 13.3$ across the entire redshift range over $z = 0.002 - 0.423$ for absorbers with Doppler parameter $b \leq 40$ km s^{-1}, and better than $N(\text{H I}) = 13.1$ over $z = 0.02 - 0.243$. Lyα absorbers at $z > 0.423$ are found in the FOS spectra retrieved from the HST data archive. The bottom panel shows the cumulative N(H I) distribution of the absorbers. Right: Redshift distribution of galaxies with $R \leq 20$ in the field around PKS0405−123. The top panel shows all galaxies over the 1600 arcmin^2 sky area centered at roughly at the background QSO, for which we have obtained robust redshift measurements. The bottom panel shows galaxies within 1 h^{-1} Mpc comoving radius in each redshift bin. In both panels, the open histogram represents galaxies of all spectral types, the shaded histogram represents emission-line dominated galaxies, and the solid curve shows the selection function of our redshift survey, which is 90% complete at $R = 20$.

estimate of the N(H I) threshold below which the Lyα absorbers no longer trace the large-scale galaxy structures.

2. THE LYα-ABSORBER AND GALAXY SAMPLES

Exquisite echelle spectra of the QSO PKS0405−123 ($z_{\rm qso} = 0.5726$) have been obtained by the STIS GTO team (PID = 7576), using the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST) with a $0.2'' \times 0.06''$ slit and the E140M grating ($R = 45,800$ or 6.7 km s^{-1}) for a total exposure time of 27,208 s. The final stacked spectrum covers a spectral range spanning from 1140 to 1730 Å and has on average $S/N \approx 7$ per resolution element over the entire spectral region. Additional spectra obtained using the Faint Object Spectrograph (FOS) have been included for finding strong absorption lines log $N(\text{H I}) > 14$ outside of the STIS/E140M spectral range at $0.423 \leq z_{\rm Ly\alpha} \leq 0.557$. Detailed data reduction and absorption line measurements are presented in Williger et al. (2005). We have identified 112 Lyα absorption lines with log $N(\text{H I}) = 12.5 - 16.5$ at greater than 4-σ significance level over $0.01 < z_{\rm Ly\alpha} < 0.54$. The redshift distribution and cumulative N(H I) distribution functions of the Lyα absorber sample along this sightline are presented in the left panels of Figure 1.

We have carried out a redshift survey of galaxies in the field around PKS0405−123, using the WFCCD multi-slit spectrograph mounted on the 2.5 m du Pont telescope at the Las Campanas Observatory. The primary goal of the project is to study the large-scale correlation between galaxies and QSO absorption-line systems at low redshift. We therefore aim to obtain a complete, magnitude-limited survey of galaxies over a field size that is comparable to the characteristic correlation length of field galaxies at $z \sim 0.2$. Detailed descriptions of the galaxy survey and reduction of the spectroscopic data are presented in Prochaska et al. (2005, in preparation). In summary, we have observed 535 galaxies of R-band magnitude $R \leq 20$ over a 1600-arcmin^2 non-contiguous region centered on the background QSO. Robust redshift measurements are available for 482 of these galaxies. Our survey is sensitive to galaxies of 0.4 L_* at $z = 0.2$ within 5 h^{-1} Mpc comoving radius from the QSO lines of sight.[†]

The redshift distribution of all 482 galaxies identified in the field around PKS0405−123 is presented in the top-right panel of Figure 1 . Redshifts are determined using multiple spectral line features identified in the data. Typical redshift measurement errors are $\Delta z = \pm 0.0002$ or ~ 40 km s^{-1}. We also perform a χ^2 analysis, which compares the galaxy spectra with a model established from a linear combination of four principal components from the Sloan Digital Sky Survey galaxy sample (Schlegel et al. 2005, in preparation). This procedure allows us to characterize each galaxy based on its emission- and absorption-line properties. We found that 284 of all galaxies in our survey have emission-line dominated spectral features. The redshift distribution of 61 galaxies found within a comoving radius of $\rho = 1$ h^{-1} Mpc from the QSO line of sight is presented in the bottom-right panel of Figure 1 . The shaded histogram represents emission-line galaxies, while

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[†] Throughout the paper, we adopt a Λ cosmology, $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$, with a dimensionless Hubble constant $h = H_0/(100\ \text{km s}^{-1}\ \text{Mpc}^{-1})$.

the open histogram represents all galaxies identified in the same volume. The solid curve in each panel shows the selection function of our survey.

3. ANALYSIS

3.1. *The Galaxy-Absorber Cross-correlation Function*

In the formalism developed by Mo & White (1996), the halo-mass cross-correlation function $\xi_{hm}(r)$ is related to the mass auto-correlation function $\xi_{mm}(r)$ by a mass-dependent bias $b(M)$, as $\xi_{hm}(r) = b(M)\,\xi_{mm}(r)$. Comparing the amplitudes of the galaxy-absorber cross-correlation function ξ_{ga} and the galaxy auto-correlation function ξ_{gg} therefore yields an estimate of the absorber halo mass, if the mean halo mass of the galaxies is known. This approach, which has been applied to study the origin of intermediate-redshift Mg II absorbers (Bouché, Murphy, & Péroux 2004), has an important advantage in that the complicated selection function of a galaxy survey impacts both ξ_{ga} and ξ_{gg} in the same way and is therefore cancelled out in the calculation.

In principle, the correlation function is multi-variate. It depends on the velocity separation between galaxy-absorber or galaxy-galaxy pairs v along the line of sight, the comoving projected distance of a pair ρ, and the underlying halo mass of the source, for which we use the spectral properties of the galaxies as a proxy. In agreement with previous findings of Lanzetta, Webb, & Barcons (1997), who considered ξ_{ga} as a function of v and ρ, we find that $\xi_{ga}(v)$ measured from the sample of 112 Lyα absorbers and 482 galaxies identified along the sightline toward PKS0405−123 weakens toward larger ρ and shows no signal beyond $\rho = 1\,h^{-1}$ Mpc. Here we focus on a 1-D correlation function measured versus v, and consider only pairs at $\rho \leq 1\,h^{-1}$ Mpc. We compare $\xi_{ga}(v)$ measured for Lyα absorbers of different $N(\mathrm{H\ I})$ with $\xi_{gg}(v)$ measured separately for all galaxies, absorption-line dominated galaxies, and emission-line dominated ones (Figure 2). Error bars in each velocity separation bin are estimated assuming Poisson statistics.

3.2. *Clustering of* Lyα *Absorbers with Galaxies of Different Spectral Morphology*

Three distinct features are qualitatively apparent in the left panels of Figure 2. First, a strong cross-correlation signal in $\xi_{ga}(v)$ for Lyα absorbers of $\log N(\mathrm{H\ I}) > 13.5$ is present over velocity separation $v < 250$ km s^{-1}. The signal has $> 4-\sigma$ level of significance when compared with random galaxy and absorber pairs found at large velocity separation along the sightline, confirming that these absorbers are not randomly distributed with respect to galaxies. Second, this cross-correlation signal in $\xi_{ga}(v)$ becomes weaker for absorbers of lower $N(\mathrm{H\ I})$, suggesting a correlation between $N(\mathrm{H\ I})$ and the mass scale of the underlying dark matter halos traced by these absorbers. In addition, the absence of a cross-correlation signal for Lyα absorbers of $\log N(\mathrm{H\ I}) < 13.5$ indicates that these weak absorbers do not trace the spatial distribution of galaxies. Third, we find that when considering all galaxies together the amplitude in ξ_{gg} is more than 50% stronger than the amplitude in ξ_{ga}, even for the strong absorbers in the top panel. This is consistent with previous findings, which have been interpreted as Lyα absorbers tracing large-scale filamentary structures rather than individual galactic halos (e.g. Grogin & Geller 1998; Tripp et al. 1998).

To examine the nature of Lyα absorbers, we repeat the analysis including galaxies of different spectral properties. We divide the galaxies into two subsamples depending on whether their spectra are dominated by absorption or emission features. Our choice is guided by the fact that absorption-line dominated galaxies are more strongly clustered than emission-line dominated galaxies (e.g. Madgwick et al. 2003). The results of the correlation analysis including only absorption-line and only emission-line dominated galaxies are presented respectively in the middle and right panels of Figure 2. We find that $\xi_{ga}(v)$ measured using only absorption-line dominated galaxies is consistent with zero on all velocity separation scales for the entire Lyα absorber sample, contrary to the enhanced ξ_{gg} measured for absorption-line dominated galaxies only. In addition, we find that $\xi_{ga}(v) = 6.2 \pm 1.9$ for Lyα absorbers of $\log N(\mathrm{H\ I}) \geq 14$ and emission-line galaxies are consistent with $\xi_{gg}(v) = 6.6 \pm 0.8$ for emission-line galaxies to within 1-sigma uncertainties, indicating that these strong Lyα absorbers and emission-line dominated galaxies found in our redshift survey trace the same halo population. The weaker $\xi_{ga}(v)$ at lower $N(\mathrm{H\ I})$ observed in the right panels also suggests that weaker absorbers may originate in still lower mass halos that are loosely clustered with these known galaxies.

3.3. $N(\mathrm{H\ I})$*-Dependent Clustering Strength of* Lyα *Absorbers with Galaxies*

Much of the past dispute regarding the nature of Lyα absorbers originates in the different $N(\mathrm{H\ I})$ regimes considered by different authors. It appears that while most strong absorbers of $N(\mathrm{H\ I}) \geq 14$ can be explained by the known galaxy population (e.g. Chen et al. 1998, 2001), the majority of weaker absorbers remain as a poor tracer of galaxies (e.g. Penton et al. 2002, 2004). This is also observed in the declining cross-correlation amplitude with $N(\mathrm{H\ I})$ as presented in Figure 2. We perform a maximum likelihood analysis to obtain a quantitative estimate of the $N(\mathrm{H\ I})$ threshold below which the Lyα absorbers no longer trace known galaxies.

We first formulate the cross-correlation function as

$$\xi_{ga}(v) = A\,\times\,\left(\frac{N(\mathrm{H\,I})}{N_0} - 1\right)^{\beta} \times\,\exp\left[-\frac{1}{2}\left(\frac{v}{v_0}\right)^2\right] \quad (1)$$

if $N(\mathrm{H\ I}) \geq N_0$ and $\xi_{ga}(v) = 0$ otherwise. We model the velocity dispersion function of the galaxy and absorber pairs using a gaussian of FWHM v_0. According to the model described in Equation (1), we expect that the cross-correlation amplitude is scaled with $N(\mathrm{H\ I})$ for absorbers of $N(\mathrm{H\ I}) \geq N_0$ following a power-law function, and vanishes for weaker absorbers. For each Lyα absorber i of $N^i(\mathrm{H\ I})$ at $z^i_{\mathrm{Ly}\alpha}$, the probability of finding a galaxy j within the volume defined by $z^i_{\mathrm{Ly}\alpha} \pm \Delta z$ and $\rho_j \leq 1\,h^{-1}$ Mpc is then written as

$$P_i(z^j_{\mathrm{gal}}) = \frac{\left\{1 + A\times\left(\frac{N^i(\mathrm{H\,I})}{N_0} - 1\right)^{\beta} \times \exp\left[-\frac{1}{2}\left(\frac{v_{ij}}{v_0}\right)^2\right]\right\} \times \Delta z}{\int \mathcal{S}(z) \times \left\{1 + A\times\left(\frac{N^i(\mathrm{H\,I})}{N_0} - 1\right)^{\beta} \times \exp\left[-\frac{1}{2}\left(\frac{v(z_{\mathrm{gal}} - z_{\mathrm{Ly}\alpha})}{v_0}\right)^2\right]\right\} dz}, \quad (2)$$

where $v_{ij}/c = [(1+z_{\mathrm{gal}})^2 - (1+z_{\mathrm{Ly}\alpha})^2]/[(1+z_{\mathrm{gal}})^2 + (1+z_{\mathrm{Ly}\alpha})^2]$ and $\mathcal{S}(z)$ is the redshift selection function

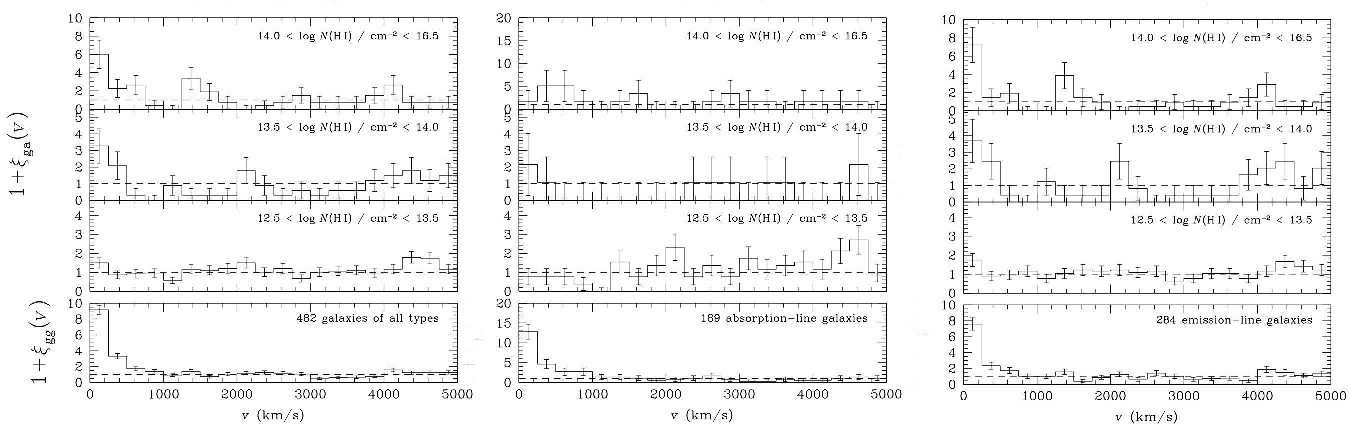

FIG. 2.— Galaxy-Lyα absorber cross-correlation function $\xi_{ga}(v)$ versus velocity separation v of each pair along the line of sight in the top three panels for Lyα absorbers of different N(H I), and galaxy-galaxy auto-correlation function $\xi_{gg}(v)$ versus v in the bottom panel. We note that the limits on the y-axis for weak absorbers has been rescaled for a better visibility of the cross-correlation signal at $v < 500$ km s^{-1}. For ξ_{ga}, we consider all 61 galaxies found within $\rho = 1\ h^{-1}$ Mpc co-moving radius to the sightline in the left panels, and 15 absorption-line dominated and 46 emission-line galaxies at $\rho < 1\ h^{-1}$ Mpc in the middle and right panels, respectively. For ξ_{gg}, we consider all pairs of different spectral type with a co-moving impact separation $< 1\ h^{-1}$ Mpc.

of our galaxy survey within the $1\,h^{-1}$ Mpc comoving radius as presented in the bottom-right panel of Figure 1. Considering all the galaxy and Lyα absorber pairs as a whole, we can formulate the likelihood function of observing m galaxies at $\rho \leq 1\,h^{-1}$ Mpc from n Lyα absorbers of $12.5 \leq N(\mathrm{H\ I}) < 17$ as the following,

$$\mathcal{L}(A, N_0, \beta, v_0) = \prod_{i=1}^{n}\prod_{j=1}^{m} P_i(z^j_{\mathrm{gal}}). \tag{3}$$

Finally, maximizing $\mathcal{L}$ with respect to A, N_0, β, and v_0 leads to best-fit values of $A = 11 \pm 3$, $\log\ N_0 = 13.6 \pm 0.1$, $\beta = 0.0 \pm 0.1$, and $v_0 = 102 \pm 9$ km s^{-1}, where the error of each parameter represents the 68% 1-σ, 1-parameter uncertainty.

Adopting a power-law model $(N(\mathrm{H\ I})/N_0)^\beta$ with $\log\ N_0 = 13.6$ to replace the step function in Equation (1) yields a best-fit $\beta = 0.20 \pm 0.02$. The non-zero value reflects a significant difference in ξ_{ga} between strong and weak absorbers. We note, however, that the best-fit power-law model substantially underestimates ξ_{ga} at $\log\ N(\mathrm{H\ I}) \geq 14$, when extrapolating from $\log\ N(\mathrm{H\ I}) = 12.5 - 13$, and is therefore not likely to represent the intrinsic shape of ξ_{ga}. Adopting a gamma-function form following $\exp(-N_0/N(\mathrm{H\ I})) \times (N_0/N(\mathrm{H\ I}))^\beta$ yields $\log N_0 = 13.5 \pm 0.1$ and $\beta = 0.0 \pm 0.1$.

4. DISCUSSION AND CONCLUSIONS

Our pilot study of the galaxy-Lyα absorber cross-correlation function at $z < 0.5$ using galaxies and absorbers identified along the sightline toward PKS0405−123 has offered important insights for understanding the nature of Lyα absorbers over a wide range of N(H I):

First, the cross-correlation analysis not only confirms that Lyα absorbers (particularly those of $\log\ N(\mathrm{H\ I}) \geq 14$) are not randomly distributed with respect to galaxies, but also shows that emission-line dominated galaxies and these strong absorbers have comparable clustering strength. The difference in the auto-correlation amplitudes observed for absorption- and emission-line dominated galaxies confirms that absorption-line galaxies trace higher-mass halos with stronger clustering strength than emission-line galaxies. We therefore conclude that Lyα absorbers of $\log\ N(\mathrm{H\ I}) \geq 14$ and emission-line dominated galaxies found in our redshift survey do indeed trace the same halo population. A quantitative estimate of the halo mass scale traced by the Lyα absorbers will require a detailed clustering analysis of these emission-line galaxies over a large volume.

Second, we observe a likely transition in the clustering strength of Lyα absorbers with respect to galaxies at $\log\ N(\mathrm{H\ I}) = 13.6$, above which the amplitude of $\xi_{ga}(v)$ is comparable to the emission-line galaxy auto-correlation function and below which $\xi_{ga}(v)$ quickly declines to within 2.5 σ of zero. The diminishing cross-correlation signal between these weak absorbers and known galaxies suggests that they are a poor tracer of galactic structures. A detailed comparison with numerical simulations will help us to constrain the amount of baryons contained in these low-N(H I) Lyα absorbers. In addition, we do not detect a strong dependence of ξ_{ga} on N(H I) at $\log\ N(\mathrm{H\ I}) \geq 13.6$. It would be interesting to see whether ξ_{ga} remains insensitive to N(H I) with a larger galaxy and absorber pair sample over multiple lines of sight.

With a larger sample of galaxies and absorbers over multiple lines of sight, we hope to obtain a better constraint for the galaxy-Lyα absorber cross-correlation function in the near future. In addition, we will extend this analysis to O VI absorbers identified along these sightlines, in order to locate the warm-hot intergalactic medium probed by these absorbers (e.g. Mulchaey et al. 1996; Tripp, Savage, & Jenkins 2001).

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