Cross-Correlation between Damped Ly\(\alpha\) Systems and Ly-break Galaxies in Cosmological SPH Simulations

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ABSTRACT

We calculate the cross-correlation function (CCF) between damped Ly-\(\alpha\) systems (DLAs) and Lyman break galaxies (LBGs) using cosmological hydrodynamic simulations at \(z = 3\). We compute the CCF with two different methods. First, we assume that there is one DLA in each dark matter halo if its DLA cross section is non-zero. In our second approach we weight the pair-count by the DLA cross section of each halo, yielding a cross-section-weighted CCF. We also compute the angular CCF for direct comparison with observations. Finally, we calculate the auto-correlation functions of LBGs and DLAs, and their bias against the dark matter distribution. For these different approaches, we consistently find that there is good agreement between our simulations and observational measurements by Cooke et al. (2006a) and Adelberger et al. (2005). Our results thus confirm that the spatial distribution of LBGs can be well described within the framework of the concordance \(\Lambda\)CDM model, and support the argument that the distribution of DLAs is strongly correlated with that of LBGs.

Key words: cosmology: theory — stars: formation — galaxies: evolution – galaxies: formation – methods: numerical

1 INTRODUCTION

According to the cold dark matter (CDM) model of structure formation, the spatial distribution of galaxies can be understood as a result of the gravitational instability of density fluctuations in the CDM, and the dark matter halo mass function can be well described by analytic models (Sheth & Tormen 1999). More precisely, hierarchical CDM models predict that the massive galaxies at high redshift (hereafter high-\(z\)) are clustered together in high-density regions, while low-mass galaxies tend to be more evenly spaced (Bardeen et al. 1986; Kaiser 1984). Under the assumption that galaxies are produced from primordial density fluctuations owing to gravitational instability, one can estimate the average mass of galaxy host halos based on clustering data. For example, Adelberger et al. (2003) estimated the typical halo mass of LBGs at \(z \sim 3\) to be \(M_{\text{halo}} \approx 10^{13} M_\odot\) from observations of their auto-correlation function (ACF).

Damped Lyman-\(\alpha\) systems (DLAs), defined as quasar absorption systems with column density of \(N_{\text{HI}} > 2 \times 10^{20}\) atoms cm\(^{-2}\) (Wolfe et al. 1986), probe the \(\text{H}^\text{I}\) gas associated with high-\(z\) galaxies. Since stars are hardly formed in warm ionized gas and are tightly correlated with cold neutral clouds, the amount of \(\text{H}^\text{I}\) gas is very important, being the precursor of molecular clouds (Wolfe et al. 2003). DLAs dominate the \(\text{H}^\text{I}\) content of the Universe at \(z \approx 3\) and contain a sufficient amount of \(\text{H}^\text{I}\) gas mass to account for a large fraction of the present-day stellar mass (Storrie-Lombardi & Wolfe 2000). The gas kinematics and chemical abundances of DLAs can be measured and are documented in detail. However, the masses of DLA host halos (hereafter DLA halos) remain poorly constrained, because only about a quarter of all \(z > 3\) quasars exhibit DLA absorption, and the scattered distribution of DLAs in quasar sight lines precludes the use of DLAs as tracers of dark matter halo mass.

Alternatively, the mass of DLA halos can be probed by the cross-correlation between DLAs and a galaxy population whose clustering and halo mass are well understood. Cooke et al. (2006a,b) used 211 LBG spectra and 11 DLAs to measure the three dimensional (3-D) LBG ACF and DLA-LBG CCF (see also Bouche et al. 2005; Bouche & Lowenthal 2004; Gawiser et al. 2001). Their anal-

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ysis started by counting the number of LBGs in 3-D cylindrical bins centered on each of 11 DLAs, following the method of Adelberger et al. (2003). They detected a statistically significant result of DLA-LBG CCF, and estimated an average DLA halo mass of \( M_{\text{DLA}} \approx 10^{11.2} M_\odot \), assuming a single galaxy per halo.

On the theoretical side, Nagamine et al. (2007) calculated the average DLA halo mass using a series of cosmological hydrodynamic simulations with different box sizes, resolution and feedback strengths. They found a mean DLA halo mass of \( M_{\text{DLA}} = 10^{11.3} M_\odot \), which is comparable to what Cooke et al. (2006a) obtained. More recent work by Pontzen et al. (2008) also showed that the DLA cross-section is predominantly provided by intermediate mass halos, \( 10^9 < M_{\text{halo}}/M_\odot < 10^{11} \). These results motivate us to further examine the distribution of DLAs relative to that of LBGs. In this paper, we compute the DLA-LBG CCF in cosmological SPH simulations, using the sample of LBGs and DLAs obtained by Nagamine et al. (2004a,b). We compare our results with the observational results by Adelberger et al. (2003) and Cooke et al. (2006a).

Our paper is organized as follows. In Section 2 we briefly describe the features of our cosmological SPH simulations used in this paper. In Section 3 and Section 4 we describe and report the methodology, binning method, and the results for ‘unweighted’ and ‘weighted’ DLA-LBG CCF, respectively. We then discuss the projected angular correlation, we replace object 1 and 2 with DLA and LBG, the joint probability between DLA and LBG is

\[
\xi_{\text{DLA-LBG}}(r) = \frac{\langle n_{\text{DLA}} \cdot n_{\text{LBG}} \rangle}{\langle n_{\text{DLA}} \rangle \langle n_{\text{LBG}} \rangle},
\]

where \( n_{\text{DLA}} \) and \( n_{\text{LBG}} \) are the mean number densities of DLAs and LBGs, and \( \xi_{\text{DLA-LBG}}(r) \) is the cross-correlation function (CCF).

To estimate \( \xi_{\text{DLA-LBG}}(r) \), we use the method of Landy & Szalay (1993), whose variance is effectively Poisson:

\[
\xi_{\text{DLA-LBG}}(r) = \frac{D_{\text{DLA}}D_{\text{LBG}} - D_{\text{DLA}}R_{\text{LBG}} - R_{\text{DLA}}D_{\text{LBG}} + R_{\text{DLA}}R_{\text{LBG}}}{R_{\text{DLA}}R_{\text{LBG}}},
\]

where \( D_{\text{DLA}}D_{\text{LBG}} \) is the number of pairs between the two data samples of DLAs and LBGs separated by a distance \( r \pm \delta r \), and likewise for other terms. The notation “\( R_{\text{DLA}} \)” for example, represents the DLA sample that has random coordinate positions but with equivalent number density as the original data sample “\( D_{\text{DLA}} \)”.

The method of identifying DLAs in our simulations is described in detail in Nagamine et al. (2004a). Briefly, we

\[
\begin{array}{cccccc}
\text{Run} & L_{\text{box}} & N_p & M_{\text{DM}} & M_{\text{gas}} & \epsilon \\
D5 & 33.75 & 2 \times 324^3 & 8.15 \times 10^7 & 1.26 \times 10^7 & 4.17 \\
G5 & 100.0 & 2 \times 324^3 & 2.12 \times 10^9 & 3.26 \times 10^8 & 12.3
\end{array}
\]

Table 1. Simulations employed in this study. \( N_p \) is the initial particle number of gas and dark matter particles (hence \( \times 2 \)). \( M_{\text{DM}} \) and \( M_{\text{gas}} \) are the masses of dark matter and gas particles in units of \( h^{-1} M_\odot \), respectively, \( \epsilon \) is the comoving gravitational softening length in units of \( h^{-1} \) kpc, which is a measure of spatial resolution. All runs adopt a ‘strong’ galactic wind feedback model.
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Figure 1. DLA-LBG CCFs at $z = 3$ calculated with the regular unweighted method (Equation 2). The variance of CCFs computed with 10 different random seeds is shown with the cyan shade, and the open square symbols are the mean of 10 trials. The blue dashed line is the least-square fit to the open square points. The red solid line and the short and long dashed lines are the angular and 3-D best-fitting power-laws of Cooke et al. (2006a,b), respectively, and the yellow shade is their 1-$\sigma$ error range for the angular CCF.

set up a cubic grid that completely covers each dark matter halo, with the grid-cell size equivalent to the gravitational softening length $\epsilon$ of each run. We then calculate the H$\text{I}$ column density $N_{\text{HI}}$ of each pixel (i.e., a grid-cell on one of the planes) by projecting the H$\text{I}$ mass distribution, and identify those that exceed the DLA threshold of $N_{\text{HI}} > 2 \times 10^{20}$ atoms cm$^{-2}$ as ‘DLA-pixels’. This method allows us to quantify the DLA cross-section of each halo, and the number of DLA-pixel is $N_{\text{DLA}} = \sigma_{\text{DLA}} / \epsilon^2$.

Here we focus on the correlation signal at $\sim 35$ form factors computed with spherical shells, and Cooke et al. (2006a,b) reported $r_0 = 3.32 \pm 1.25 h^{-1}$ Mpc for the 3-D CCF calculated with spherical shells, and Cooke et al. (2006b) reported $r_0 = 2.91 \pm 1.0 h^{-1}$ Mpc and $\gamma = 1.21 \pm 0.4$ for the angular CCF.

Table 2. Best-fitting power-law parameters of unweighted and $\sigma_{\text{DLA}}$-weighted DLA-LBG CCFs at $z = 3$. The correlation length $r_0$ is in units of $h^{-1}$ Mpc. For comparison, Cooke (private communication) obtained $r_0 = 2.91 \pm 1.0 h^{-1}$ Mpc and $\gamma = 1.21 \pm 0.4$ for the 3-D CCF calculated with spherical shells, and Cooke et al. (2006b) reported $r_0 = 3.32 \pm 1.25 h^{-1}$ Mpc and $\gamma = 1.74 \pm 0.36$ for the angular CCF.

| Run | $r_0$ ($h^{-1}$ Mpc) | $\gamma$ |
|-----|---------------------|---------|
| D5  | 2.68                | 1.46    |
| G5  | 2.92                | 1.68    |

First, we select the LBGs that are brighter than $R_{\text{AB}} = 25.5$ magnitude in the D5 and G5 runs. There are 30 (4030) LBGs in the D5 (G5) run. Nagamine et al. (2004) have shown that the brightest galaxies with $R_{\text{AB}} < 25.5$ in our simulations satisfy the $U_{\text{GR}}$ color selection criteria for LBGs (e.g., Steidel et al. 1999). There are 22616 (25683) DLA halos with $\sigma_{\text{DLA}} > 0$ in the simulated volumes of the D5 (G5) run. The ‘random’ catalogues of LBGs and DLA halos with random positions were created with a random number generator from Numerical Recipes (Press et al. 1992). The selected LBGs were paired with DLA halos, and the number of pairs that reside in spherical shells of $[\log r, \log r + \Delta \log r]$ were counted. The maximum pair separations probed for the D5 and G5 runs are 10 and $35 h^{-1}$ Mpc, respectively, with 20 bins in a logarithmic scale of distance $r$. The periodic boundary condition was taken into account appropriately, and the pair-search was extended to the next adjacent box where needed.
simply owe to relatively small sample of LBGs in D5 and its small box-size.

Cooke et al. (2006a) published only the angular CCFs. However, they can also estimate the 3-D radial CCF using redshift information. The best-fitting parameters to the radial CCF by Cooke (private communication) using spherical shells is \( r_0 = 3.39 \pm 1.2 \text{ h}^{-1} \text{ Mpc} \) and \( \gamma = 1.61 \pm 0.3 \), which is shallower than the angular CCF results. As we will further discuss in Section 5, the method of Adelberger et al. (2003) adopts cylindrical shells at small distances, which have larger volumes than spherical shells. This allows the cylindrical shell method to contain a larger number of LBGs and DLAs at small distances, yielding a slightly steeper \( \gamma \) in Cooke et al. (2006b) compared to the above spherical shell case. We regard the comparison to the angular CCF of Cooke et al. (2006b) as the primary one, because Cooke et al. argue that the angular CCF calculated by the method of Adelberger et al. (2003) is more robust than the 3-D radial calculation with spherical shells, and the values of \( (r_0, \gamma) \) derived from both CCFs should be equivalent theoretically (see Section 6).

4 \( \sigma_{\text{DLA}} \)-WEIGHTED CCF

In Section 3, we calculated the CCF assuming that there is one DLA per halo. This assumption is valid as long as we are concerned with the CCF at scales of \( r \gtrsim 300 \text{ h}^{-1} \text{ kpc} \), because in the real observations the same dark matter halo is rarely probed by a close pair of quasars. However, Nagamine et al. (2004b, Fig. 1) showed that the DLA clouds have extended distributions in massive dark matter halos. Therefore, it may be more desirable to take the DLA cross-section of each halo into account when calculating the CCF. A simple way to achieve this is to weight the number of DLA-LBG pairs by the number of DLA-pixels of each halo. Since the displacement between DLA-pixels within a single halo is typically much smaller than the distance between LBG-DLA pairs, we do not count the individual pairs between LBG and DLA-pixels. Instead, we treat it as if all DLA-pixels are located at the halo center, and weight each DLA-pixel-pair-count by the number of DLA-pixels \( N_i \) (hereafter we drop the superscript ‘DLA’ for simplicity) and compute the \( \sigma_{\text{DLA}} \)-weighted CCF as

\[
\xi_{\text{DLA}-\text{LBG}}(r) = \frac{N_i \delta_{\text{DLA}} \delta_{\text{LBG}} - N_i \delta_{\text{DLA}} \delta_{\text{LBG}} - N_i \delta_{\text{DLA}} \delta_{\text{LBG}} + N_i \delta_{\text{DLA}} \delta_{\text{LBG}}}{N_i \delta_{\text{DLA}} \delta_{\text{LBG}}}.
\]

(3)

For the ‘random’ DLA dataset, we shuffle the original \( N_i \) list randomly and make new pairs with different DLA halos. Again, 10 realisations of the random dataset have been used to examine the statistical variance of the estimated CCF.

The results for the \( \sigma_{\text{DLA}} \)-weighted CCF is shown in Figure 2. We find best-fitting parameters equal to \( (r_0 \text{ h}^{-1} \text{ Mpc}, \gamma) = (3.35, 1.70) \) and \( (3.30, 1.69) \) for the D5 and G5 runs, respectively, as shown by the blue long-dashed line (see also Table 2). Both results show remarkable agreement with the best-fitting values of Cooke et al. (2006a) \( r_0 = 3.32 \pm 1.25 \) and \( \gamma = 1.74 \pm 0.36 \). The result of D5 is somewhat noisy at \( r \lesssim 1 \text{ h}^{-1} \text{ Mpc} \), which originates from the noisy pair-count of \( N_i \delta_{\text{DLA}} \delta_{\text{LBG}} \).

The parameter values given in Table 2 clearly show that the \( \sigma_{\text{DLA}} \)-weighted method gives larger values of \( r_0 \) and a slightly steeper power-law slope. In a CDM universe, the number of low-mass halos is far greater than that of massive halos. Therefore, even a small weighting by \( N_i \) boosts up the overall pair-count, yielding a stronger correlation signal compared to the unweighted case. The larger LBG sample in the G5 run makes its result more robust against the weighting procedure than that of the D5 run, and the slope \( \gamma \) in the G5 run does not change very much between the two calculation methods.

5 ANGULAR CROSS CORRELATION FUNCTION

In observational studies, a different method is usually used to obtain the values of \( (r_0, \gamma) \) compared with what we described in Sections 3 and 4 because the precise estimation of any LBG position along the line of sight is difficult to achieve owing to redshift uncertainties caused by peculiar velocities and galactic winds. With such imprecision, it is not possible to measure the CCF at scales \( r \lesssim 1 \text{ h}^{-1} \text{ Mpc} \) reliably. Therefore, rather than attempting to estimate the 3-D distance between DLAs and LBGs, observers usually employ the angular CCF using the projected data on the sky. For example, Cooke et al. (2006a) computed the angular CCF using the method proposed by Adelberger et al. (2003). In order to compare our results with those by Cooke et al.’s, we briefly describe the calculation method of Adelberger et al. (2003), and then describe how we perform our measurement of the angular CCF.

With a power-law assumption, the expected number of pairs for the projected angular CCF is

\[
\omega_p(r_0 < r_z) = \frac{r_z^{\gamma - 1}}{2r_0^\gamma} B\left(\frac{1}{2}, \frac{\gamma - 1}{2}\right) I_\gamma\left(\frac{1}{2}, \frac{\gamma - 1}{2}\right),
\]

(4)

where \( B \) and \( I_\gamma \) are the beta and incomplete beta functions with (e.g., Press et al. 1992)

\[
x \equiv r_z^2 (r_z^2 + r_0^2)^{-1}.
\]

(5)

Adelberger et al. (2003) proposed to count the number of pairs in cylindrical shells of angular separation \( r_0 \pm \delta r_0 \) and redshift separation \( r_z \pm \delta r_z \), rather than using spherical shells. By setting \( r_z \) to

\[
r_z = \max \left(1000 \text{ km s}^{-1} \left(1 + \frac{zr_0}{H(z)}\right), 7r_0\right),
\]

(6)

the lower limit ensures that the redshift errors do not lead to the underestimate of the number of pairs, and the upper limit allows sufficient distances to include enough correlated pairs (Adelberger et al. 2003).

For our calculations, we focus at \( z = 3 \) and thus \( r_z = \max(12.8 \text{ h}^{-1} \text{ Mpc}, 7r_0) \). With simple algebra, Equation (4) can be converted to a more familiar power-law form:

\[
\xi(r_0) = 2r_0^{\gamma - 1} \omega_p(r_0) B\left(\frac{1}{2}, \frac{\gamma - 1}{2}\right) I_\gamma\left(\frac{1}{2}, \frac{\gamma - 1}{2}\right)^{-1} = \left(\frac{r_0}{r_0}\right)^{-\gamma},
\]

(7)
where \( r_s \) is set to \( r_{\text{max}} \). We change from spherical coordinates to cylindrical coordinates, and set the number of cylindrical bins to 20 in a logarithmic scale as before. All pair searches are extended to the adjacent box using periodic boundary conditions, if appropriate.

A few assumptions must be made while we deal with the beta and incomplete beta functions. There are two parameters (\( \gamma \) and \( x \)) that must be given to calculate the values of \( B \) and \( I_x \). To calculate \( \gamma \), we first plot Equation (7) without \( B \) and \( I_x \) (i.e., \( 2r_{\text{max}}\omega_p(r_s)/r_s \)) and find the best-fitting value of \( \gamma \). The value of \( x \) is determined by \( r_s \) and \( r_0 \) as shown in Equation (8). By setting \( r_s = r_{\text{max}} \), the angular separation will be divided into two different regimes. Within the smaller angular separation range (\( 100 \, h^{-1} \, \text{kpc} < r_0 < 1.83 \, h^{-1} \, \text{Mpc} \)), the correlated pairs are counted up to the maximum radial distance of \( r_{\text{max}} = \pm 12.8 \, h^{-1} \, \text{Mpc} \) for a cylinder centered on an LBG or DLA, while in the larger separation range (\( r_0 > 1.83 \, h^{-1} \, \text{Mpc} \)) all the correlated pairs within \( r_{\text{max}} = \pm 7r_0 \) are counted. With the fixed value of \( \gamma \) obtained above and 20 different values of \( x \) for each bin, \( B \) and \( I_x \) can be calculated for each bin.

The angular CCF results of our calculations are shown in Figures 3 and 4 for both the unweighted and the \( \sigma_{\text{DLA}} \)-weighted method. The best-fitting power-law parameters are given in Table 3. Again, the agreement with the results of Cooke et al. (2006a) is quite good. Similarly to the 3-D CCF case, the \( \sigma_{\text{DLA}} \)-weighted case gives a slightly larger \( r_0 \) and steeper \( \gamma \) than the unweighted case. The unweighted case of D5 is shallow with \( \gamma = 1.42 \), but in the \( \sigma_{\text{DLA}} \)-weighted case, \( \gamma \approx 1.7 \) is recovered.

Table 3. Best-fitting power-law parameters for the angular CCF at \( z = 3 \). The units of the parameters are the same as in Table 2. For comparison, Cooke et al. (2006a) reported \( r_0 = 3.32 \pm 1.25 \, h^{-1} \, \text{Mpc} \) and \( \gamma = 1.74 \pm 0.36 \) for their angular CCF.

6 AUTO-CORRELATION FUNCTIONS

6.1 LBG auto-correlation

The auto-correlation function (ACF) also gives important constraints on the distribution of the population under study. In this section, we calculate the 3-D LBG ACF by changing all subscripts in Equation (2) to ‘LBG’:

\[
\xi_{\text{LBG-LBG}}(r) = \frac{D_{\text{LBG}}D_{\text{LBG}} - 2D_{\text{LBG}}R_{\text{LBG}} + R_{\text{LBG}}D_{\text{LBG}}}{R_{\text{LBG}}R_{\text{LBG}}}
\]

Our result for the ACF is shown in Figure 5, and the best-fitting power-law parameters are \( r_0 = 3.98 \, h^{-1} \, \text{Mpc} \) and \( \gamma = 1.55 \). The last two data points were not included for the power-law fit because they are likely underestimated owing to the limited box-size. Our values of \( r_0 \) and \( \gamma \) agree well with the observational estimates of Adelberger et al. (2003) and Adelberger et al. (2005), who measured values of \( r_0 = 4.0 \pm 0.6 \, h^{-1} \, \text{Mpc} \) and \( \gamma = 1.57 \pm 0.14 \) for the LBG ACF at \( z \approx 3 \), with a correction for the integral constraint. This correction owes to the finite size of the observed field.
of-view, and it must be added to the computed correlation function as follows:

$$\xi'(r) = \xi(r) + IC,$$

where $\xi'(r)$ and $\xi(r)$ are the corrected and computed ACF, respectively, and IC is the integral constraint. Following the method described in Adelberger et al. (2005) and Lee et al. (2006), we calculate the value of IC and find that it is not significant in our simulations compared to our computed ACF value. Therefore, we neglect the correction by IC in this paper.

The dark matter ACF (the red filled triangles in Figure 5) was also computed as described in Nagamine et al. (2008) in order to calculate the bias of LBGs against the dark matter distribution (see Section 7).
6.2 DLA auto-correlation

Similarly to the LBG ACF, it would be useful to compute the DLA ACF in order to estimate the DLA host halo mass. In this section, we calculate the DLA ACF with both the unweighted and the $\sigma_{\text{DLA}}$-weighted methods. By replacing all subscripts to ‘DLA’ in Equations (5) and (6), we obtain

$$\xi_{\text{DLA-DLA}}(r) = \frac{D_{\text{DLA}}D_{\text{DLA}} - 2D_{\text{DLA}}R_{\text{DLA}} + R_{\text{DLA}}^2}{R_{\text{DLA}}^2},$$

(10)

and

$$\xi_{\text{DLA-DLA}}^{\text{weighted}}(r) = \frac{N_i N_j D_{\text{DLA}}^2 - 2N_i N_j D_{\text{DLA}} R_{\text{DLA}} + N_i N_j R_{\text{DLA}}^2}{N_i N_j R_{\text{DLA}}^2},$$

(11)

where $N_i N_j D_{\text{DLA}}^2$ and $N_i N_j D_{\text{DLA}} R_{\text{DLA}}$ are the numbers of data-data pairs and data-random pairs, weighted by the number of DLA pixels $N_i$ and $N_j$. As before, ten different realisations of random dataset have been used to examine the statistical variance.

Our DLA ACF result is shown in Figure 6 and we find the best-fitting power-law parameters of $r_0 = 2.43 h^{-1}$ Mpc and $\gamma = 1.60$ for the unweighted ACF, and $r_0 = 2.99 h^{-1}$ Mpc and $\gamma = 1.55$ for the $\sigma_{\text{DLA}}$-weighted ACF, as summarized in Table 4. The values of $\gamma$ are similar to those for the LBG ACF with $\gamma \approx 1.6$, but $r_0$ is much smaller. This is owing to the lower average DLA halo mass compared to the LBG host halos, as we will discuss further in Section 7.

7 BIAS AND HALO MASSES

Comparing the correlation functions of DLAs and LBGs with that of dark matter gives the measure of ‘bias’ for the spatial distribution of these populations against that of dark matter. Figure 7 shows the bias, defined as $b \equiv \sqrt{\xi/\xi_{\text{DM}}}$, as a function of distance $r$, where $i =$ LBG or DLA. This definition is based on the linear bias model,

$$\xi_i(r) = b_i^2 \xi_{\text{DM}}(r).$$

(12)

The corresponding expression for the cross-correlation is (Gawiser et al. 2001)

$$\xi_{\text{DLA-LBG}}(r) = b_{\text{DLA}} b_{\text{LBG}} \xi_{\text{DM}}(r).$$

(13)

Therefore, the two lines for the CCF in Figure 7 are in fact showing $\sqrt{\xi_{\text{DLA-LBG}}}$, as indicated on the axis on the right-hand-side. Taking the ratio of the above two expressions gives (Cooke et al. 2006a)

$$\frac{\xi_{\text{DLA-LBG}}}{\xi_{\text{LBG}}} = b_{\text{DLA}} b_{\text{LBG}}^{-1}.$$  

(14)

In all cases shown in Figure 7 the bias slowly decreases with increasing distance. The upturn at $r = 20 h^{-1}$ Mpc for the LBG ACF is probably just noise. We take a simple average of bias values across the logarithmic bins at $r = 1.40 - 14.5 h^{-1}$ Mpc, and find $b = 2.60, 2.47, 2.30, 2.24$ and 1.93 for LBG ACF, LBG-LBG CCF ($\sigma_{\text{DLA}}$-weighted), DLA ACF ($\sigma_{\text{DLA}}$-weighted), DLA-LBG CCF (unweighted), and DLA ACF (unweighted), respectively. The values of $r_0$ also reflect the sizes of average bias values. We took the above range of scales for taking the average because most of the recent observations are probing the scale of $r \approx 1 - 10 h^{-1}$ Mpc.

Adelberger et al. (2003) used the results of Adelberger et al. (2003) to obtain an average bias of $b_{\text{LBG}} = 2.5 \pm 0.4$ for LBGs at $z \sim 3$. Our average bias value of 2.60 for the LBG ACF is very close to that of Adelberger et al. (2003), and at the lower end of the estimate of $b_{\text{LBG}} = 3.0 \pm 0.5$ by Lee et al. (2006).

The model of Sheth & Tormen (1999) shows that an understanding of the unconditional mass function can provide an accurate estimation of the large-scale bias factor. From our average bias, we calculate the mean halo mass for LBGs and DLAs (using the unweighted and the $\sigma_{\text{DLA}}$-weighted results) based on the method described in Mo & White (2002), as shown in Table 4. Our calculation

\begin{table}
\centering
\begin{tabular}{lll}
\hline
 & $r_0$ & $\gamma$ \\
\hline
LBG-auto & 3.98 & 1.55 \\
DLA-auto (unweighted) & 2.43 & 1.60 \\
DLA-auto ($\sigma_{\text{DLA}}$-weighted) & 2.99 & 1.55 \\
\hline
\end{tabular}
\caption{ACFs of LBGs and DLAs for the G5 run. The results of unweighted and $\sigma_{\text{DLA}}$-weighted methods are given for the DLA ACF. $r_0$ is in units of $h^{-1}$ Mpc. For comparison, Adelberger et al. (2003) reported $r_0 = 4.0 \pm 0.6 h^{-1}$ Mpc and $\gamma = 1.57 \pm 0.14$ for the LBGs at $z \sim 3$.}
\end{table}

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of LBG halo mass is very close to that by Adelberger et al. (2003), $M_{\text{halo}} = 10^{11.2} - 10^{11.6} M_\odot$ [yellow shade in Fig. 7], which is very encouraging. Finally, Bouche & Lowenthal (2005) estimated $(\log M_{\text{DLA}}) = 11.13 \pm 0.13$ from observations and $(\log M_{\text{DLA}}) = 11.16$ from simulations. These values are somewhat higher than the upper limit of our unweighted DLA halo mass and very close to our $\sigma_{\text{DLA}}$-weighted one. Cooke et al. (2006a) also obtained a similar value of $M_{\text{halo}} \simeq 10^{11.2} M_\odot$.

Alternatively, we can directly calculate the mean DLA halo mass using the simulation result without going through the bias argument. For the G5 run, the mean is $\langle M_{\text{halo}} \rangle = 11.5$ and $\langle \log M_{\text{DLA}} \rangle = 11.3$. These values are somewhat higher than the mean halo mass reported in Table 5. However, the values of $\langle M_{\text{halo}} \rangle$ in Table 5 are computed from the average bias within the range of $r = 1.40 - 14.5 h^{-1}$ Mpc, and they could become higher if we included the bins at smaller scales. Since observers probe mostly $r \lesssim 1 - 10 h^{-1}$ Mpc, the values reported in Table 5 are more appropriate for comparison with observations.

Bouche & Lowenthal (2004) defined the parameter $\alpha$ as the ratio of correlation functions: $\alpha \equiv \xi_{\text{CCF}}(M_{\text{DLA}})/\xi_{\text{ACF}}(M_{\text{LBG}})$. If the value of $\alpha$ is larger (or smaller) than unity, then the mean halo mass of DLAs is more (or less) massive than that of the LBGs. The ratio of the average bias of LBG ACF and DLA-LBG CCF is $\alpha = 0.742$ for our results. This value is in good agreement with the observational estimates of $\alpha = 1.62 \pm 1.32$ (Bouche & Lowenthal 2004), $\alpha = 0.73 \pm 0.08$ (Bouche et al. 2004), and $\alpha = 0.771$ (Mo & White 2002).

8 DISCUSSION AND CONCLUSIONS

Our study represents a first attempt to calculate the DLA-LBG cross-correlation function at $z = 3$ using cosmological SPH simulations. We calculated the DLA-LBG CCFs in several different approaches: 3-D, angular, unweighted, and $\sigma_{\text{DLA}}$-weighted. We also computed the auto-CF of LBGs and DLAs, and the bias against dark matter. In comparison to observational data by Adelberger et al. (2003); Cooke et al. (2006a), we find good agreement between our simulations and observational measurements. Our results suggest that the spatial distribution of DLAs and LBGs are strongly correlated.

Let us summarize some of the main conclusions of this work. In the first part of this paper, our results on the 3-D CCF calculated with spherical shells (Table 2) are to be compared with the 3-D spherical shell result by Cooke (private communication), $r_\gamma = 3.39 \pm 1.2 h^{-1}$ Mpc, and $\gamma = 1.61 \pm 0.3$. Our results are consistent with Cooke’s within the error. The shallow slope of Cooke’s above estimate probably owes to the limited sample size in the spherical shell at small distances, as we discussed in Sections 3 and 5.

In the second part, we have replaced the spherical shell method with the projected approach used in Adelberger et al. (2003) and Cooke et al. (2006b), and calculate the best-fitting values given in Table 3. Encourag-
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Figure 7. The biases of all correlation functions at \( z = 3 \) that we computed in this paper for the G5 run. The tick marks on the left-hand-side show the host halo masses calculated with the method described in \( \text{Mo & White (2002)} \). The yellow shade shows the upper and lower limits by \( \text{Adelberger et al. (2005)} \).

Finally, our results are within the upper and lower limits of the observational measurement by \( \text{Cooke et al. (2006a,b)} \).

Finally, we also analyzed the auto-correlation functions of LBGs and DLAs at \( z = 3 \) (Table 3) found in our simulations. Our results for the best-fitting parameters of the LBG ACF agree well with \( \text{Adelberger et al. (2005)} \). We calculated the integral constraint and confirmed that it was not significant. Our result show that LBGs are more strongly correlated than DLAs, and have higher mean halo mass.

Figure 8 summarizes the best-fitting power-law parameters for all the correlation functions that we obtained in the earlier sections. In most cases, the slope \( \gamma \) falls into the range \( 1.5 - 1.7 \) and the variation is not very large. The correlation length \( r_0 \) shows a much larger variation from \( 2.5 \, h^{-1} \text{Mpc} \) to \( 4 \, h^{-1} \text{Mpc} \), depending on the sample and calculation method. This trend is similar to that seen by \( \text{Cooke et al. (2006b, Fig. 8)} \). In general, the \( \sigma_{DLA} \)-weighted method gives a larger \( r_0 \) than the unweighted method, and the D5 run tends to underestimate the value of \( \gamma \) owing to the small LBG sample size.

Finally, the LBG bias, derived from the LBG ACF in Section 7, has led to the upper and lower limits of the LBG dark matter halo mass of \( \log(M_{h,\text{halo}}) = 11.48^{+0.31}_{-0.22} \) (see Table 3). This result is consistent with observational estimates of the LBG halo mass of \( M_{h,\text{halo}} \sim 10^{12} M_\odot \), e.g., \( \text{Adelberger et al. (1998), Steidel et al. (1998)} \) and within the limit of \( M_{h,\text{halo}} = 10^{11.2} - 10^{11.8} M_\odot \) (Adelberger et al. 2005). Similarly, we derived the DLA biases, and obtained the mean DLA halo masses as shown in Table 3 (Cooke et al. 2006a, b)’s measurement showed a DLA galaxy bias of \( b_{DLA} \sim 2.4 \) and an average DLA halo mass of \( M_{h,\text{DLA}} \sim 10^{11.2} M_\odot \). Our average DLA bias and halo mass estimates are in good agreement with theirs. We also examined the ratio of bias values defined as \( \alpha \equiv \frac{b_{CCF}}{b_{ACF}} \) (Bouche & Lowenthal 2004), and found that our value of \( \alpha = 0.742 \) agrees well with the observational estimates. This again shows that the mean halo mass of DLAs is less than that of the LBGs.

The fact that \( \langle M_{h,\text{DLA}} \rangle \) is greater than \( \langle M_{h,\text{halo}} \rangle \) is a natural outcome because the LBG sample is limited to the bright star-forming galaxies with \( R_{AB} < 25 \) and \( M_\star \sim 10^{10} - 10^{11} M_\odot \), whereas the DLA \( H_\alpha \) gas is present in numerous lower mass halos below the LBG threshold. Given the good agreement between our results and the observations, and considering all the accumulated evidence that suggests a high halo mass for LBGs (e.g., \( \text{Adelberger et al. (1998), Baugh et al. (1998), Giavalisco et al. (1998), Katz et al. (1999), Kauffmann et al. (1999), Mo & Fukugita (1999), Mo et al. (1999), Papovich et al. (2001), Sharpley et al. (2001), Steidel et al. (1998)} \), we conclude that scenarios where the majority of LBGs are merger-induced starburst systems associated with low-mass halos (Lowenthal et al. 1997, Sawicki & Yee 1998, Somerville et al. 2001, Weatherley & Warren 2003) no longer appear to be viable models for LBGs.

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