MEASUREMENT OF THE SPATIAL CROSS-CORRELATION FUNCTION OF DAMPED Lyα SYSTEMS
AND LYMAN BREAK GALAXIES

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Received 2005 September 19; accepted 2005 November 16; published 2005 December 12

ABSTRACT
We present the first spectroscopic measurement of the spatial cross-correlation function between damped Lyα systems (DLAs) and Lyman break galaxies (LBGs). Analysis of deep uBVRI imaging of nine QSO fields with 11 known \( z \sim 3 \) DLAs has spectroscopically confirmed 211 \( z > 2 \) LBGs to \( R = 25.5 \). We find strong evidence for an overdensity of LBGs near DLAs versus random, the results of which are similar to that of LBGs near other LBGs. A maximum likelihood cross-correlation analysis finds the best-fit value for the correlation length to be \( r_0 = 2.9^{+0.4}_{-0.3} \) h\(^{-1}\) Mpc using a fixed value of \( \gamma = 1.6 \). The implications of the DLA-LBG clustering amplitude on the average dark matter halo mass of DLAs are discussed.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — quasars: absorption lines

Online material: color figures

1. INTRODUCTION
Over the last two decades, quasar (QSO) absorption-line systems have provided tremendous insight into the nature of protogalaxies at high redshift. Of particular interest are the damped Lyα systems (DLAs), defined to have \( N(\text{H} \, \text{i}) \geq 2 \times 10^{20} \) atoms cm\(^{-2}\) (Wolfe et al. 1986, 2005). Systems with such large column densities can provide self-shielding from the ambient ionizing radiation at high redshift and protect large reservoirs of neutral gas. These reservoirs are prime sites for star formation. Moderate- and high-resolution DLA databases (e.g., Prochaska et al. 2001, 2003) and numerous spectroscopic studies have given us a detailed view of the chemical abundances and gas kinematics of protogalaxies, yet except for two confirmed \( z > 2 \) detections of DLA emission (Möller et al. 2002, 2004), information regarding their mass, luminosity, and morphology has remained elusive.

One approach to measure the average mass of a galaxy population at high redshift operates under the implicit assumption that galaxies are a result of the gravitational instabilities of primordial density fluctuations. Cold dark matter (CDM) hierarchical models predict that the most massive galaxies at high redshift preferentially formed clustered together near the density peaks of regions with an underlying mass overdensity, whereas low-mass galaxies formed more uniformly throughout space (Kaiser 1984; Bardeen et al. 1986). The factor by which the underlying dark matter is enhanced in the regions where galaxies cluster as compared with that implied by the galaxies themselves is referred to as bias. In this context, the spatial distribution of a population of galaxies provides a means to infer their typical dark matter halo mass. This method has been used to infer the average mass of Lyman break galaxies (LBGs) at \( z \sim 3 \) (e.g., Steidel et al. 1998; Adelberger et al. 1998) and agrees with mass estimates from nebular line-width measurements (Pettini et al. 2001) and those implied by fits to models of star formation (Shapley et al. 2001).

It is difficult to measure the mass of DLAs by their spatial clustering, because of the sparse distribution of bright QSO sight lines and because only approximately a quarter of all \( z > 3 \) QSOs exhibit DLA absorption. However, the mass of DLAs can be inferred from their cross-correlation with another known population (Gawiser et al. 2001). Since the LBG auto-correlation function and LBG galaxy bias at \( z \sim 3 \) have been established (Adelberger et al. 2003, hereafter A03), it is natural to use these galaxies as tracers of the underlying mass distribution to cross-correlate with \( z \sim 3 \) DLAs. A03 used the spectroscopic sample of Steidel et al. (2003) to test the spatial distribution of LBGs and DLAs. A count of the number of LBGs in three-dimensional cells centered on the four DLAs in their sample showed no significant overdensity. In contrast, Bouche & Lowenthal (2004) used photometric redshifts to measure the clustering of LBGs near two DLAs and one sub-DLA in wide-field images. From Monte Carlo simulations, they found a nonzero DLA-LBG clustering amplitude to greater than \( 2 \sigma \), and an angular analysis on scales of \( \sim 5-15 \) h\(^{-1}\) Mpc estimated the DLA-LBG cross-correlation to be equal to or greater than the LBG autocorrelation. Both analyses had limited statistics, and neither could confirm or rule out a significant overdensity of LBGs near DLAs.

In this Letter, we highlight the results of a spectroscopic survey for LBGs associated with 11 DLAs at \( z \sim 3 \). We intro-
duce strong evidence for an overdensity of LBGs near DLAs and present the first detection of the three-dimensional DLA-LBG cross-correlation function. A more complete discussion of the DLA-LBG cross-correlation analysis will be presented in a forthcoming publication (Cooke et al. 2006), along with our independent measurement of the $z \sim 3$ LBG autocorrelation function. In this Letter, we adopt a $\Omega_m = 0.3$, $\Omega_k = 0.7$ cosmology.

2. OBSERVATIONS

We acquired deep $u'BVRI$ images from 2000 April through 2003 November of nine QSO fields with 11 known DLAs (2.78 < z < 3.32) using the Carnegie Observatories Spectrograph and Multiobject Imaging Camera (Kells et al. 1998) on the 200 inch (5 m) Hale Telescope at Palomar and the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I Telescope. The data were reduced in a standard manner. We developed a $u'BVRI$ photometric selection technique for LBGs at $z \sim 3$ that proved comparable to previous techniques in both efficiency and resulting redshift distribution. Over the 465 square arcminutes surveyed, we found 796 objects that met our color criteria. Follow-up multiobject spectroscopy of 529 LBG candidates using LRIS yielded 339 redshifts. We identified 211 LBGs with $z > 2$ and used these in the cross-correlation analysis. More information about the data acquisition, reduction, and analysis can be found in Cooke et al. (2005).

3. CLUSTERING ANALYSIS

3.1. Evidence of an LBG Overdensity near DLAs

As a coarse measure of the distribution of LBGs near DLAs, we divided our survey volume into cells with dimensions of the field area of LRIS at $z \sim 3$ ($\sim 7 \times 10$ h$^{-1}$ Mpc) and $\Delta z = 0.025$ ($\sim 17$ h$^{-1}$ Mpc). The choice of cell size follows that of Adelberger et al. (1998) and A03 and includes the majority of the objects associated with a central object having a galaxy bias less than or equal to the LBG bias at $z \sim 3$. The extended length in the redshift direction is intended to account for the $\sim 1–2$ h$^{-1}$ Mpc error in the systemic redshift measurement inherent to LBGs.

This simple counts-in-cells analysis found an average of 1.27 objects residing in cells centered on each of the 11 DLAs, where an average of 0.85 objects should have been found randomly. Random values were determined for objects in identical cells at the redshifts of the DLAs pulled from normalized random catalogs that mimicked the constraints of the data and were corrected by the photometric selection function (see Cooke et al. 2005, 2006). This observed overdensity can be compared with an average of 1.16 objects found in cells of identical size centered on LBGs in our survey having similar redshifts to the DLAs but located in other fields. Interestingly, two of the 14 objects associated with the DLAs are QSOs. Since QSOs are believed to form in massive dark matter halos that seed supermassive black holes, this suggests that the corresponding DLAs reside in overdense regions.

3.2. DLA-LBG Cross-Correlation Function

We measured the DLA-LBG cross-correlation function, $\xi_{DLA-LBG}$, using the usual approach of comparing galaxy pair separations in the data with galaxy pair separations in random galaxy catalogs. We used the estimator of Landy & Szalay (1993) to measure the excess probability over random of finding an LBG at a distance $r$ from a DLA:

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

where $D_{DLA}D_{LBG}$ is the catalog of data-data pair separations, $D_{DLA}R_{LBG}$ and $R_{DLA}D_{LBG}$ are the data-random and random-data pair separation cross-reference catalogs, and $R_{DLA}R_{LBG}$ is the catalog of random-random pair separations. This estimator is well suited for small galaxy samples and has a nearly Poisson variance. The random catalogs were constructed to be many times larger than the data catalog in order to reduce shot noise and were then normalized to the data. The mean LBG density was determined from the data in all 11 fields. We determined $\xi(r)$ by counting the number of pairs in each catalog over a series of logarithmic or linear intervals (i.e., bins). In addition, we made the assumption that $\xi(r)$ follows a power law of the form

$$\xi(r) = (r/r_{0})^{-\gamma}.$$

3.3. Conventional Binning

We initially measured the correlation function by duplicating the cylindrical binning technique described in Appendix C of A03. This technique was adopted to help minimize the effect that LBG redshift uncertainties have on the clustering signal as compared with traditional radial bins. In addition, this approach permitted a direct comparison of our results with the published values of A03 using the available online data set$^4$ of Steidel et al. (2003), since both surveys were executed in a similar manner and used the same instruments and configurations.

In this treatment, the expected projected angular overdensity is defined to be

$$\omega_p(r) = \frac{r^2}{2\pi} \cdot B(\frac{1}{2}, \frac{\gamma - 1}{2}) I(\frac{1}{2}, \frac{\gamma - 1}{2}),$$

where $r_c$ is the greater of (1000 km s$^{-1}$)/(1 + $z$)/H(z) and 7$r_g$ and B and I are the beta and incomplete beta functions with $x \equiv r^2/(r_c^2 + r_g^2)$ (Press et al. 1992). Applying this method to the DLA-LBG cross-correlation, we found best-fit parameter values and 1$\sigma$ uncertainties of $r_g = 3.3 \pm 1.3$ h$^{-1}$ Mpc, $\gamma = 1.7 \pm 0.4$. Figure 1 presents and compares the results with the DLA-LBG autocorrelation results of A03 and is plotted in a consistent manner with that work, where $r_{\max}$ as described above. The errors on the cross-correlation values shown in the figure are those determined using the formulation of Landy & Szalay (1993), and the reported errors on the functional fit were determined by duplicating the Monte Carlo error analysis as described in A03. The latter error analysis may underestimate the true error by a factor of $\sim 1–2$ (Adelberger et al. 2005).

Although the uncertainties are large, it is immediately apparent from Figure 1 that the form and central values of the two correlation functions are similar. In addition, we computed a cross-correlation length of $r_0 = 3.5 \pm 1.0$ h$^{-1}$ Mpc for a fixed

4 See http://vizier.cfa.harvard.edu/viz-bin/VizieR?source=J/ApJ/592/728.
value of $\gamma = 1.6$, the value reported in A03 and Adelberger et al. (2005) for the LBG autocorrelation. Our decision to center the DLAs in the observed fields prevented an estimation of the DLA-LBG cross-correlation effectively beyond \( \sim 4 \) h\(^{-1}\) Mpc using the above method. However, our cross-correlation values are consistent with the constraints placed on the DLA-LBG cross-correlation by Bouche\' & Lowenthal (2004) using a comparable method over a range of \( \sim 5-15 \) h\(^{-1}\) Mpc. [See the electronic edition of the Journal for a color version of this figure.]

### 3.4. Maximum Likelihood

As an independent method of analysis, and to make the most of our data set, we determined the maximum likelihood of a power-law fit (eq. [2]) to the observed data (e.g., Croft et al. 1997; Mullis et al. 2004). We divided the radial separations into a large number of finely spaced regular intervals that coincided with either one or zero LBGs. Poisson statistics hold in the regime of large interval number and small probability per interval. We used this to form the likelihood function

$$
\mathcal{L} = \prod_{i}^{N} \frac{e^{-\mu_{i}} \mu_{i}^{n_{i}}}{n_{i}!} \prod_{i \neq j}^{N} \frac{e^{-\mu_{j}} \mu_{j}^{n_{j}}}{n_{j}!},
$$

(4)

where $\mu_{i}$ is the expected number of pairs in the $i$th interval, $n_{i}$ is the observed number of pairs for that same interval, and the index $j$ runs over the elements where there are no pairs. The expected number of pairs was determined by solving equation (1) for $D_{\text{DLA}} D_{\text{LBG}}$ over a reasonable range of $r_{0}$ and $\gamma$. We then maximized the expression $S = -2 \ln \mathcal{L}$. Confidence levels were defined as $\Delta S = S(r_{0,\text{best}}, \gamma_{\text{best}}) - S(r_{0}, \gamma)$ with the assumption that $S$ has a $\chi^{2}$ distribution. We found the best-fit values and 68% confidence levels for the cross-correlation using this method to be $r_{0} = 2.8^{+1.4}_{-1.0}$ h\(^{-1}\) Mpc and $\gamma = 2.1^{+1.3}_{-0.4}$ with a best-fit value of $r_{0} = 2.9^{+1.2}_{-1.0}$ h\(^{-1}\) Mpc for a fixed value of $\gamma = 1.6$ (smaller diamond) is shown with the associated 1 $\sigma$ uncertainty on $r_{0}$. For comparison, the square and error bars indicate the LBG autocorrelation best-fit values and 1 $\sigma$ uncertainties of 4.0 \pm 0.6 h\(^{-1}\) Mpc, $\gamma = 1.6 \pm 0.1$ from Adelberger et al. (2005). Here the angular positions of the galaxies in the random catalogs were made to be identical to the data to minimize possible artificial clustering effects caused by the physical constraints of the slit masks. [See the electronic edition of the Journal for a color version of this figure.]

### 4. DISCUSSION

The LBG bias at $z \sim 3$, derived from the LBG autocorrelation of the $R < 25.5$ spectroscopic sample, has led to an average

![Figure 1](image1.png)

**Fig. 1.**—Measurement of the DLA-LBG cross-correlation following the binning and correlation method of Adelberger et al. (2003) and plotted in a consistent manner. The cross-correlation values are indicated by diamonds, and the best fit of $r_{0} = 3.3 \pm 1.3$ h\(^{-1}\) Mpc, $\gamma = 1.7 \pm 0.4$ is indicated by the solid line. The errors shown are near-Poisson, and the reported errors are where 68% of the best-fit values lie from a Monte Carlo analysis of the functional fit. For a fixed value of $\gamma = 1.6$, we find a best-fit correlation length of $r_{0} = 3.5 \pm 1.0$ h\(^{-1}\) Mpc. The LBG autocorrelation (squares) of Adelberger et al. (2003) are overlaid over a similar scale with the published fit of $r_{0} = 3.96 \pm 0.29$ h\(^{-1}\) Mpc, $\gamma = 1.55 \pm 0.15$ (dotted line). The DLA-LBG cross-correlation values are consistent with the angular wide-field analysis of Bouche\' & Lowenthal (2004) that was most effective on larger scales (\(\sim 5-15\) h\(^{-1}\) Mpc). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 2](image2.png)

**Fig. 2.**—Two-parameter probability contours for the DLA-LBG cross-correlation using the maximum likelihood method. The best fit-values of $r_{0} = 2.8^{+1.4}_{-1.0}$ h\(^{-1}\) Mpc, $\gamma = 2.1^{+1.3}_{-0.4}$ are indicated by the larger diamond. The best-fit value of $r_{0} = 2.9^{+1.2}_{-1.0}$ h\(^{-1}\) Mpc for a fixed value of $\gamma = 1.6$ (smaller diamond) is shown with the associated 1 $\sigma$ uncertainty on $r_{0}$. For comparison, the square and error bars indicate the LBG autocorrelation best-fit values and 1 $\sigma$ uncertainties of 4.0 \pm 0.6 h\(^{-1}\) Mpc, $\gamma = 1.6 \pm 0.1$ from Adelberger et al. (2005). Here the angular positions of the galaxies in the random catalogs were made to be identical to the data to minimize possible artificial clustering effects caused by the physical constraints of the slit masks. [See the electronic edition of the Journal for a color version of this figure.]

Cooke et al. (2006) will describe the above analyses in more detail, present several tests to address the shortcomings of each method, and make efforts to quantify the physical effects that the multiobject slit masks have on the clustering signal.

A short summary of best-fit values and 1 $\sigma$ uncertainties described here and from that work is provided in Table 1. It can be seen that all independent methods, and tests thereof, result in consistent central values within their uncertainties.

### TABLE 1

**DLA-LBG Cross-Correlation Parameter Summary**

| Method                          | $r_{0}$     | $\gamma$  |
|---------------------------------|-------------|------------|
| Conventional binning$^{ab}$     | 3.32 ± 1.3  | 1.74 ± 0.4 |
| Maximum likelihood$^{c,d,e}$    | 2.81^{+1.4}_{-1.1} | 2.11^{+1.4}_{-1.3} |
| Cumulative $\chi^{2}$ test$^{d,e}$ | 3.84^{+1.2}_{-1.1} | 2.06^{+1.2}_{-1.1} |
| Conventional binning$^{f}$      | 3.21 ± 1.0  | 2.03 ± 0.2  |
| Maximum likelihood$^{f}$        | 3.20^{+1.0}_{-1.0} | 1.62^{+1.0}_{-1.0} |
| Cumulative $\chi^{2}$ test$^{f}$ | 3.91^{+1.3}_{-1.3} | 2.11^{+1.3}_{-1.3} |

$^{a}$ Galaxy separations determined using the cylindrical approach described in Adelberger et al. (2003), Appendix C.

$^{b}$ Angular positions of galaxies in the random catalogs are identical to the angular positions of the data (to minimize possible artificial clustering effects caused by the slit masks).

$^{c}$ Galaxy separations determined radially.

$^{d}$ Described in Cooke et al. (2006).

$^{e}$ Angular positions of galaxies in the random catalogs are random.
LBG dark matter halo mass of $\sim 10^{12} M_\odot$ (e.g., Steidel et al. 1998; Adelberger et al. 1998). The 11 DLAs presented here constitute an unbiased representation of a random cross section weighted sample. The similarity between the LBG autocorrelation and the DLA-LBG cross-correlation implies that the bias factors of the two populations are comparable and that DLAs, on average, may form in similarly massive potential wells. We consider the implications from the best-fit central value $r_0 \sim 2.9$ using the maximum likelihood method with fixed $\gamma = 1.6$. This measurement corresponds to a DLA galaxy bias of $b_{DLA} \sim 2.4$ and represents an average DLA halo mass of $\langle M_{DLA} \rangle \sim 10^{11.2} M_\odot$, assuming a single galaxy per halo. This value is higher than what is predicted for DLAs by simple models (e.g., Mo et al. 1998) but is in very good agreement with numerical models of varying resolution that invoke strong galactic-scale winds (Nagamine et al. 2005) and thermal feedback (Maller et al. 2001; Bouche et al. 2005). In these models, galactic outflows purge low-mass halos of gas capable of generating damped Ly$\alpha$ absorption lines and result in a higher mean mass. It must be noted that because CDM predicts a steeply rising mass function, it is expected that the median DLA halo mass is lower than the mean mass implied here.

The observed similarity in the spatial distributions of DLAs and LBGs helps support previous ideas that the two populations may be connected (Schaye 2001; Möller et al. 2002). Recent analysis of the Hubble Ultra Deep Field (H.-W. Chen & A. M. Wolfe 2006, in preparation) shows little evidence for in situ star formation throughout the DLA neutral gas. However, calculations using the C ii$^+$ absorption feature to trace the cooling rates in DLAs (Wolfe et al. 2003) require local sources of radiation to heat DLAs. A plausible scenario is that LBGs are embedded in the same systems that contain DLAs. This model is reinforced by the near-equality between DLA cooling rates and LBG heating rates. Furthermore, the lack of detected DLA emission out to reasonable impact parameters from background QSOs and the above implied average halo mass are consistent with DLAs sampling the bulk of the LBG population with typical impact parameters of less than 1$''$ and median luminosities of $R_\alpha > 27$.

Although the uncertainties in this initial measure of the three-dimensional DLA-LBG cross-correlation function are large, there remains strong evidence for an overdensity of LBGs near DLAs. The similarity in the central values between the DLA-LBG cross-correlation and the LBG autocorrelation underscores a need for additional observations to improve the statistical significance of these results and to provide a step toward a complete picture of galaxy formation and evolution.

We would like to thank K. L. Adelberger and C. Mullis for helpful and informative discussions. This work was partially supported by National Science Foundation grant AST 03-07824 and NSF Astronomy and Astrophysics Postdoctoral Fellowship grant AST 02-01667 awarded to E. G.

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