The Oxford-Dartmouth Thirty Degree Survey II: Clustering of Bright Lyman Break Galaxies - Strong Luminosity Dependent Bias at z=4

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ABSTRACT

We present measurements of the clustering properties of bright (L > L*) z∼4 Lyman Break Galaxies (LBGs) selected from the Oxford-Dartmouth Thirty Degree Survey (ODT). We describe techniques used to select and evaluate our candidates and calculate the angular correlation function which we find best fitted by a power law, \( \omega(\theta) = A_w \theta^{-\beta} \) with \( A_w = 15.4 \) (with \( \theta \) in arcseconds), using a constrained slope of \( \beta = 0.8 \). Using a redshift distribution consistent with photometric models, we de-project this correlation function and find a comoving \( r_0 = 11.4^{+1.7}_{-1.0} h^{-1}100 \) Mpc in a \( \Omega_m = 0.3 \) flat Λ cosmology for \( i_{AB} \leq 24.5 \). This corresponds to a linear bias value of \( b = 8.1^{+2.0}_{-2.6} \) (assuming \( \sigma_8 = 0.9 \)). These data show a significantly larger \( r_0 \) and \( b \) than previous studies at \( z \sim 4 \). We interpret this as evidence that the brightest LBGs have a larger bias than fainter ones, indicating a strong luminosity dependence for the measured bias of an LBG sample. Comparing this against recent results in the literature at fainter (sub-\( L_* \)) limiting magnitudes, and with simple models describing the relationship between LBGs and dark matter haloes, we discuss the implications on the implied environments and nature of LBGs. It seems that the brightest LBGs (in contrast with the majority sub-\( L_* \) population), have clustering properties, and host dark matter halo masses, that are consistent with them being progenitors of the most massive galaxies today.

Key words: surveys – galaxies: high-redshift – galaxies: evolution – galaxies: fundamental parameters – galaxies: statistics

1 INTRODUCTION

The study of the universe at very high redshifts has expanded rapidly over the last decade. It is now possible to observe galaxies over more than 90% of the age of the Universe. One of the most significant breakthroughs has been the discovery of a population of strongly-clustered, star forming galaxies at 2.5 < z < 4.5, using the Lyman-break technique pioneered by Steidel & Hamilton (1992). It is possible to select significant numbers of these galaxies using deep ground based multi-colour imaging (e.g., Steidel et al. 1996).

Lyman Break Galaxies (LBGs) represent the largest known population of high redshift objects, and therefore present a window into an important stage in the formation of galaxies and large-scale structure. Much is now known about their physical characteristics (Pettini et al. 2001, Shapley et al. 2001, 2003). They are somewhat dusty starburst galaxies with star formation rates in the range 10-100s M_☉ yr⁻¹ contributing a highly significant fraction of the stars formed at z ∼ 2.5–5 (Adelberger & Steidel 2000).

Comparison of their clustering properties and number

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densities with semi-analytic models suggests that they are either relatively small galaxies, experiencing brief and infrequent bursts of star formation that are primarily driven by galaxy-galaxy mergers (‘The Collisional Starburst Model’; Somerville, Primack, & Faber 2001), or in very massive environments with large reservoirs of gas, becoming massive $L*$ galaxies today (‘The Massive Halo Model’; Steidel et al. 1998; Baugh et al. 1998).

Although these scenarios have been tested against models of galaxy formation using the LBG angular correlation function on different scales, and as a function of luminosity (Bullock, Wechsler, & Somerville 2002; Wechsler, Somerville, Bullock, Kolatt, Primack, Blumenthal, & Dekel 2001), the results are still somewhat dependent on the observational sample used. Correlation scale measurements range from $r_0 = 2–12\,h^{-1}_{100}\,\text{Mpc}$ (Adelberger et al. 1998; Giavalisco et al. 1998; Steidel et al. 1998; Arnouts et al. 1998; Giavalisco & Dickinson 2001; Ouchi et al. 2001; Adelberger et al. 2003; Foucaud et al. 2003). The range is likely due in part to cosmic variance because of relatively small sample sizes and may also reflect the luminosity dependence of clustering and the effects of small scale clustering.

The data, (especially in the more studied $z \sim 3$ population) do not yet provide unequivocal answers. Porciani & Giavalisco (2002) find a lack of power in the angular correlation function on small scales suggesting few LBG close pairs. Giavalisco & Dickinson (2001) and Foucaud et al. (2003) find fainter LBGs less strongly clustered than brighter ones. Conversely, the clustering results at $z \sim 4$ of Ouchi et al. (2001) imply an excess of LBG close pairs from which they estimate an LBG merger rate. Using $z \sim 3$ clustering data provided by Adelberger et al., several authors (Somerville et al. 2001; Wechsler et al. 2001; Bullock et al. 2002) have shown that the collisional starburst type models are marginally more favourable than massive halo models. However it seems clear that current data sets are not extensive enough, and do not have accurate enough photometric redshifts in large samples, to provide very strong constraints on the relationship between LBGs and their host dark matter haloes. To begin to explore these questions it is useful to have very wide and deep multi-band imaging, to optimise the selection and redshift determination for many thousands of LBG candidates, over a range in absolute magnitudes. The ODT is one such survey.

The structure of this paper is as follows. In §2 we present the ODT survey, and its salient characteristics. The candidate selection techniques, and their limitations, are discussed in §3. The general statistical properties of $z \sim 4$ LBGs are presented in §4 and the projected and spatial correlation functions are the topic of §5. These results are placed in a theoretical context, focusing on the nature of the environments in which LBGs exist in §6 the main conclusions finally being drawn in §7. Throughout this paper we use AB magnitudes, and assume a $(\Omega_m,\Omega_{\Lambda},\sigma_8) = (0.3,0.7,0.9)$ cosmology, unless otherwise stated, with $H_0 = 100\,h_{100}\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

![Figure 1](https://example.com/fig1.png)

**Figure 1.** Filter curves for the full set of filters employed in the ODT Survey, convolved with the chip QE curve.

2 THE OXFORD-DARTMOUTH THIRTY DEGREE SURVEY

The Oxford-Dartmouth Thirty Degree Survey (ODT) is a deep-wide survey using the Wide Field Camera (WFC) on the 2.5-m Isaac Newton Telescope (INT) at La Palma. The survey employs six broad-band filters in $UBVRI'Z$, and the transmission curves are provided in Figure 1. When completed the survey will cover $\sim 30$ square degrees in $BVI'Z$ to $R_{90} = 25.25$ in four fields of $5 - 10$ deg$^2$ each. The coordinates of these four fields are provided in Table 1. Presently, approximately 25 deg$^2$ of the survey have been observed in $BVI'Z$, although only data from the Andromeda field are analysed in detail here. The $U$ data has only been observed in the best conditions, and currently covers $\sim 1$ deg$^2$, all of which is in the Andromeda field. We are currently undertaking a $K$-band survey to $K_{90} \approx 18.5$ using the 1.3-m McGraw-Hill Telescope at the MDM Observatory on Kitt Peak (Olding 2002). The three largest fields are also covered at radio frequencies with the VLA in $A$ and $D$ array at 1.4GHz, and the Lynx field is covered by low frequency radio observations with the VLA in $A$ array at 74MHz and 330MHz. In addition, we are able to obtain redshifts for several sources in the survey which are part of the Texas-Oxford One-Thousand (TOOT) redshift survey of radio sources (Hill & Rawlings 2003).

Whilst the ODT survey has a number of scientific aims, one of the principal projects is the detection of large numbers of LBGs (at $z \sim 4$) over a wider field than previous studies. The ODT survey reaches depths comparable to previous studies of LBGs (e.g. Steidel et al. 1999; Ouchi et al. 2001) but over a significantly larger area of sky (c.f. 9000 square arcmin in Ouchi et al. 2001). The ODT therefore provides an ideal data set for the selection of a sample of the brightest LBGs.

The fields discussed in this paper were observed with the 2.5-m INT during August 1998 and September 2000. Approximate 5$\sigma$ (isophotal) depths for the data along with exposure times are shown in Table 2. The median seeing for these observations is $\sim 1.1''$.

The reduction of CCD frames was carried out using the IRAF package and photometry calibrated for each frame by observing fields of Landolt (1992) on photometric nights. The thinned chips in the INT WFC mean that fringing of sky lines becomes a problem in $i'$, $Z$, and to a lesser extent, $R$ data. Fringing was removed from each image in turn by using a fringe frame generated by the combination of...
individual images for each chip. This method was successful for the $i'$ and $R$-band data, but the $Z$-band data have more significant fringing, and little of the acquired data has been incorporated to date. Image detections were carried out using the SExtractor package (Bertin & Arnouts 1996), although we chose to use our own background subtraction method, due to significant background gradients present in some of our images.

Each WFC pointing was arranged in a diagonal grid to cover each field, with several overlaps between adjacent pointings. This allows objects in overlays to be matched and a common photometric zeropoint to be applied to each field, using the method of Glazebrook et al. (1994). This method was used to obtain a common zeropoint for the $V$-band data which has the smallest scatter between chips and is not afflicted by fringing from sky lines.

In order to obtain consistent colours throughout the survey, photometry for other bands was corrected relative to the $V$-band data. This was done by minimising the deviation of the colours of ODT stellar objects from the colours of stars from Pickles (1998) in the colour-colour plane. The ODT survey and our data reduction process is described in more detail in MacDonald et al. (2004).

### Table 1

| Field     | $\alpha$(J2000) | $\delta$(J2000) | $l$ | $b$ |
|-----------|-----------------|-----------------|-----|-----|
| Andromeda* | 00 18 24        | +34 52 00       | 115 | -27 |
| Lynx†      | 09 09 45        | +40 50 00       | 181 | +42 |
| Hercules*   | 16 39 30        | +45 24 00       | 70  | +41 |
| Virgo      | 13 40 00        | +02 30 00       | 330 | +62 |

| Filter | Exposure Time | 5-σ Limit |
|--------|---------------|-----------|
| $U$    | 6x1200s       | 26.0      |
| $B$    | 3x900s        | 26.0      |
| $V$    | 3x1000s       | 25.5      |
| $R$    | 3x1200s       | 25.3      |
| $i'$   | 3x1100s       | 24.5      |
| $Z$    | 1x600s        | 22.5      |

### Table 2

| Filter | Exposure Time | 5-σ Limit |
|--------|---------------|-----------|
| $U$    | 6x1200s       | 26.0      |
| $B$    | 3x900s        | 26.0      |
| $V$    | 3x1000s       | 25.5      |
| $R$    | 3x1200s       | 25.3      |
| $i'$   | 3x1100s       | 24.5      |
| $Z$    | 1x600s        | 22.5      |

### 3.1 Models of High-z Galaxy Colours

In order to define our selection criteria for LBG candidates we plot colours for model galaxies (see Figures 2 and 3) using extended Coleman, Wu, & Weedman (1981) empirical spectral templates convolved with the INT WFC filter set. We consider two different regimes; selection using $B - V/V - i'$ colours, and selection with $B/R/R - i'$ colours. In addition, we plot stellar colours using the stellar SED library of Pickles (1998). Galaxy colours are also adjusted for absorption from the IGM using the method of Madau (1995).

This attenuation of flux due to the opacity of the IGM proves to be a significant contributor to the final observed colours of high-z objects. In addition to these empirical templates, we also compare with the model grids of Stevens & Lacy (2001), which are based on the Pegase models of Fio & Rocca-Volmerange (1997) and the standard stars of Landolt (1992), again using our INT filter set.

These models contain SEDs with a range of starburst and star formation histories along with different amounts of dust. However they compare favourably with the simple model colours shown in Figures 2 and 3. The colours of $z \sim 4$ objects are dominated by the effects of the Lyman break, and LBGs occupy essentially the same region of colour space in both models.

In order to efficiently select high redshift objects, we define the following colour-colour cuts based upon the model galaxy colours shown in Figure 2 for $B - V/V - i$ selection. For $-1.0 < (V - i') < 0.41$,

$$B - V > 1.2.$$  \hspace{1cm} (1)

For $0.41 < (V - i') < 2.3$,

$$B - V > 0.95 \times (V - i') + 0.81.$$ \hspace{1cm} (2)

Objects with $(V - i') < -1.0$ and $(V - i') > 2.3$ are excluded.
For $B - R/R - i$ selection, we use the following colour cuts based on Figure 3:

For $-1.0 < (R - i') < -0.07$,

$$ (B - R) > 1.25. $$

(3)

For $-0.07 < (R - i') < 0.9$,

$$ (B - R) > 3.25 \times (R - i') + 1.5. $$

(4)

Objects with $(R-i') < -1.0$ and $(R-i') > 0.9$ are excluded.

### 3.2 Colour-Colour Selection

Colours for a small subsection of the ODT survey are shown in Figures 4 and 5 along with the LBG selection region in colour-colour space. We also require a detection in the $V$, $R$ and $i'$ bands, increasing the probability of only detecting real objects close to the faint limits of the survey. In addition, only candidates fainter than $i' = 23.0$ are considered in order to reduce contamination from lower redshift ellipticals with similar colours to LBGs [Steidel et al. 1999]. Finally, candidates that have $B > 25.5$ or are not detected by SExtractor in $B$, are treated as non-detections and are given an limiting magnitude of $B = 25.5$.

Given that we have 4-band information available to us, we impose the additional criterion that the object lies in the selection regions of both $B - V/V - i'$ and $B - R/R - i'$ (Figures 4 and 5). Since the surface densities of objects are much higher just outside the selection region than just inside, low redshift objects are much more likely to be scattered into the selection region than vice-versa. This is somewhat reduced by requiring that an object is selected in both planes, and indeed we obtain candidate surface densities comparable to other searches for $z \sim 4$ objects (see Figure 5). The contamination of the sample, and the effects of this restriction are discussed further in the next section.

### 3.3 Contamination

Although our selection criteria are fairly conservative, contamination of a non-spectroscopic sample such of this is expected. The prime candidates for contamination are foreground Galactic stars, high redshift quasars, and most importantly, elliptical galaxies with $0.2 < z < 1.1$. Spectroscopic follow-up of a sample selected using similar selection criteria by [Steidel et al. 1999] confirmed that about 20% of candidates were in fact elliptical galaxies at intermediate redshifts. The peak of the luminosity function for elliptical galaxies with $z \sim 0.7$ corresponds to galaxies with $i' \sim 22.0$ [Bell et al. 2004]. Having a bright cut-off of $i' = 23.0$ for the sample should reduce contamination from these objects significantly, although a number of faint potential contaminants are expected to remain. In the next Section, we consider two faint limits of $i' = 24.0$ and $i' = 24.5$, and so estimate contamination levels for both limits here.

In Figures 4 and 5, the elliptical track is noticeably more extended than for other types. Objects in the range $0.2 < z < 1.1$ are both close enough, and faint enough, to scatter into the LBG selection region. In order to estimate the potential level of contamination from these objects, we simulate their expected colours by combining their colours.
Clustering of Bright Lyman Break Galaxies in the ODT Survey

Figure 4. B − V versus V − i' colours for ODT data. For clarity, only 5000 randomly chosen objects are shown. The resulting colour distribution is representative of the full data set. All objects with detections in V, R, and i' down to the limits of the survey (Table 2) are shown. Objects with no B detection are shown as red arrows. Stellar objects are designated by blue open stars, these were selected using SExtractor’s stellarity parameter, and objects with stellarity > 0.8 and R < 23.0 are plotted. All other objects are shown as black circles. The stellar locus is clearly visible and this provides a useful cross-check of the photometric consistency between fields. The selection region determined from the models discussed in section 3.1 is bounded by the black solid line.

Figure 5. As Figure 4 but using the B − R versus R − i' colours for a 5000 object subset from the ODT.

from an SED with typical photometric errors. We then normalise their numbers with an appropriate luminosity function, and test how many objects would meet our selection criteria. To obtain the colours of elliptical galaxies we use the SED from Coleman et al. (1980), as plotted in Figures 2 and 3. The expected number of galaxies can then be obtained by integrating the galaxy luminosity function using (Gardner 1998):

\[ n(m, z) dmdz = \frac{\Omega}{4\pi} \frac{dV}{dz} \phi(m, z) dmdz, \]

where \( \phi(m, z) \) is the galaxy luminosity function, and \( dV/dz \) is the comoving volume element at redshift \( z \). We use the R-band luminosity function for elliptical galaxies from the ESO-Sculptor survey at \( z \sim 0.5 \) (de Lapparent et al. 2003). The rest-frame R-band and redshift range covered by this luminosity function compares favourably to the objects of interest here. Little, or no evolution of the luminosity function is expected in our redshift range of interest (Bell et al. 2004).

To simulate photometric errors, a random error is generated using a probability distribution describing the typical error as a function of magnitude. The error in each band is then added to the respective magnitude. If just one combination of colours is used (especially \( B − V/V − i' \)), then the contamination can be quite considerable (up to 27%, see Table 3). However, by requiring that LBGs meet both selection criteria (\( B − V/V − i' \) and \( B − R/R − i' \)), the expected contamination from intermediate redshift galaxies can be reduced significantly. For \( i' < 24.0 \) we find a contamination of 4%, and for \( i' < 24.5 \) we obtain 3%.

The ODT Andromeda field (i.e. the data discussed in this paper) has a fairly low Galactic latitude of \( l = -27^\circ \), and therefore Galactic stars must be considered as potential contaminants. At the magnitudes considered here, the SExtractor star-galaxy classifier (in general) fails to distinguish cleanly between stellar and galactic light profiles. In particular, red stars are prone to be found in the selection window due to extreme intrinsic colours, or because they lie close to the selection window and are scattered in because of photometric errors, or a combination of both. In order to estimate the contamination due to stars, a model of the Galaxy (Robin & Creze 1986; Robin et al. 1996) is used to generate a mock catalogue\(^1\) of Galactic stars at the Galactic latitude and longitude of the ODT Andromeda field. This model contains elements from the thin and thick disk, along with the spheroid of the Galaxy, and a simple model of Galactic extinction (Robin & Creze 1986). The V-band number counts generated by this model were compared with the ‘Bahcall-Soneira’ model (Bahcall 1986), and with stellar number counts over the range \( 18 < V < 22 \) from the data itself, and found to be consistent.

The model produces (without photometric errors) the expected mixture of stars at given Galactic coordinates in Johnson-Cousins UBVRI, (Vega) magnitudes. These were then transformed to the ODT UBVRI\' (AB) system and combined with a function to simulate a typical photometric error in each band, as done for the simulated galaxies. Our selection criteria were then applied to these stars. In total, 17 stars (in one square degree) are found to match the selection criteria.

\(^1\) http://www.obs-besancon.fr/www/modele/
criteria to $i' = 24.5$, 7 of which have $i' < 24.0$. Given the surface densities of LBG candidates (see Section 3.3), this corresponds to a contamination of 8% for $i' < 24.0$, and 5% for $i' < 24.5$. We note that, again, these results increase significantly if only $B - V/V - i'$ or $B - R/R - i'$ selection is used (see Table 3).

Finally, using the quasar luminosity function at $z \sim 4$ (Fan et al. 2001), we expect that even if all high-$z$ quasars were to have colours consistent with LBGs, their expected number densities make any contamination from this population negligible. Our final contamination levels are therefore 12% for $i' < 24.0$, and 8% for $i' < 24.5$. The contamination results are summarised in Table 3. These results compare favourably with other LBG surveys (e.g. Ouchi et al. 2001), although the overall contamination level is reduced through the advantage of having two sets of selection criteria. Objects are less likely to be scattered into both selection windows through photometric errors than just one. We also note that our observed surface densities are fully consistent with other surveys (see Section 3.3), implying similar levels of contamination and completeness.

### 3.4 The ODT LBG Samples

This paper uses the first 2 square degrees of ODT data in the Andromeda field, which was the first part of the ODT survey to be reduced and analysed. Unfortunately the quality and depth of the survey is variable, and we restrict the data used in this paper to those regions with the best seeing. In order to reduce contamination from any spurious signal caused by field-to-field variations we consider two samples of data, one to $i' < 24.5$, and the other to $i' < 24.0$. These were chosen to provide a contiguous area covered by all colours to the required depth, where we are confident of consistent completeness in all bands. When fields overlap, the overlap regions are split equally (in R.A.) between the two fields, and objects in the region will have photometry measured from one of the fields.

The properties of the fields used (including depths) are summarised in Table 4 and Table 5 summarises the properties of the two selected samples. All five pointings are used in the bright ($i' < 24.0$) sample. These cover a region with good seeing and a completeness beyond the required $i' < 24.0$. The distribution of these objects is shown in Figure 6. After removal of satellite trails, overlaps, diffraction spikes, and bright objects, the total area covered is 0.83 deg$^2$. This sample consists of 74 objects. The ‘faint’ ($i' < 24.5$) sample, consists of just one INT WFC pointing covering 676 arcmin$^2$ (Field 1012 in Table 5). The distribution of these objects is shown in Figure 6. This sample is made up of 66 objects.

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**Table 3.** Summary of expected contamination for stars and elliptical galaxies. The contamination fraction can be significantly reduced by using both selection criteria.

| Magnitude Range | Stars | Ellipticals | Total |
|-----------------|-------|------------|-------|
| $i'$            | $BV'i'$ | $BR'i'$ | Both |
| 23.0 – 24.0     | 22% | 30% | 8% |
| 23.0 – 24.5     | 20% | 28% | 5% |

**Table 4.** Data for ODT Andromeda fields used in this paper. These fields form a single contiguous field. (a) Field name. (b) RA of field centre. (hms) (c) Dec of field centre. (dms) (d) seeing (averaged over $BV'i'$ bands). (e) Area in square arcminutes (after removal of bad areas of the chip, bright stars, satellite trails etc.). (f) Number of LBGs with $i' < 24.0$. The final four columns give the magnitude at which the total number counts turn over in each field. *Field used for the $i' < 24.5$ LBG sample.

| Field* | RA | Dec | Seeing | Area | $N_{LBG}^i$ | B | V | R | $i'$ |
|--------|----|-----|--------|------|------------|---|---|---|-----|
| I012   | 00 11 38.47 | +35 39 36.7 | 0.95 | 675.7 | | 22 | 25.8 | 25.1 | 25.1 | 24.7 |
| I013   | 00 13 49.66 | +35 45 47.8 | 1.07 | 460.7 | | 9 | 25.7 | 25.1 | 24.6 | 24.4 |
| I015   | 00 16 02.41 | +35 51 51.3 | 1.24 | 424.7 | | 10 | 25.5 | 25.0 | 25.0 | 24.5 |
| I026   | 00 10 29.80 | +35 03 39.3 | 1.09 | 538.7 | | 18 | 25.5 | 24.6 | 24.8 | 24.5 |
| I029   | 00 18 19.46 | +35 34 47.4 | 1.16 | 458.8 | | 15 | 25.5 | 25.1 | 25.0 | 24.4 |

**Table 5.** Summary of ‘bright’ and ‘faint’ LBG samples selected from the ODT.

| Sample | Limit ($i'$) | Fields | Number | Total Area |
|--------|--------------|--------|--------|-----------|
| Bright | 24.0         | All    | 74     | 0.81 deg$^2$ |
| Faint  | 24.5         | I012   | 66     | 676 arcmin$^2$ |
Figure 6. The distribution of our ‘bright’ sample of LBG candidates, with $23 < i' < 24$. The outlines of the chips which make up the INT wide field camera pointings for this mosaic are shown.

Figure 7. The distribution of our ‘faint’ sample of LBG candidates, with $23 < i' < 24.5$. The outlines of the 4 chips which make up the INT wide field camera are shown.

4 GENERAL PROPERTIES OF LBGS

4.1 Redshifts

Although the primary selection criterion for LBG candidates is the effect of the integrated opacity by intergalactic H I, redshifts are an important part of the analysis and interpretation of such samples. Obtaining spectroscopic redshifts for more than a very small fraction of our LBG candidates is not currently forthcoming, and represents a major challenge for current instrumentation, even on 8–m class telescopes.

However, in this paper, their most important use is in their statistical distribution, $N(z)$, and the corresponding selection function. This is used for deprojecting the angular correlation function to retrieve the spatial correlation function $\xi(r)$, and for detailed studies of the effects of different dark matter halo occupation function parameterisations on the global statistics, but not for the selection of LBG candidates.

4.2 The Selection Function

The selection function, as represented by the redshift distribution, is approximated by a simple analytic model based on the combined results from the colour-colour diagrams in Figures 2 and 3 and the models of Stevens & Lacy (2001). The main use of our redshift distribution will be the deprojection of the angular correlation function to obtain $r_0$ (Section 5), and we model redshift distributions using:

$$N(z) = \frac{1}{\sqrt{2\pi}\sigma_z^2}\exp\left[-\frac{(z - \bar{z})^2}{2\sigma_z^2}\right],$$

(6)

where $\bar{z}$ is the mean, and $\sigma_z$ is the standard deviation.

We find that $\bar{z} = 4.0$ and $\sigma_z = 0.2$ is a reasonable fiducial set of values that reproduces the photometrically-determined distributions. In order to test the dependence of $r_0$ on $N(z)$, we also consider other selection functions with varying mean redshifts, $\bar{z}$, and dispersions, $\sigma_z$, as well as modelling the redshift distribution as a simple top-hat function. These selection functions are shown in Figure 8. However, as we discuss in Section 5.2, at these redshifts, the deprojected $r_0$ we obtain is quite insensitive to the $N(z)$ used. We do not propagate systematic errors from the uncertainty in $N(z)$ in what follows.

4.3 Surface and Space Densities

The surface density of objects is calculated by selecting out the regions contaminated by bright stars, chip edge-effects, satellite trails, exceptionally poor seeing and strong remnant fringe effects. The sample selection described here is performed in the $i'$-band, requiring detection in the $R$ and $V$ bands as well. The measured surface densities, with Poisson uncertainties, are given in Table 6 and shown in Figure 9. In calculating these surface densities we only use those images that are both deep enough and have good seeing as described in Section 3.2. Figure 9 indicates that the ODT LBG surface densities compare well to other work (Steidel et al. 1999; Ouchi et al. 2001). We also calculate the space density using:

$$n_\Sigma = A_\Omega \Sigma \left[ \int_0^\infty N(z) \frac{dV}{dz} dz \right]^{-1},$$

(7)

where $\Sigma$ is the measured surface density in arcmin$^{-2}$, as shown in Figure 8. We use $N(z)$ from Eq. 6 and $dV(z)$ is the comoving differential volume element per square stera- dian for the cosmology of choice. The coefficient $A_\Omega = 1.1818 \times 10^7$ arcmin$^2$ sr$^{-2}$. The calculated surface and space densities are presented in Table 6. In the next Section we
5 CORRELATION FUNCTIONS

5.1 Angular Correlation Function

One of the more important results to come from LBG studies has been the measure of their angular correlation function, and associated $r_{\text{e}}$ and bias parameter, $b'$. It has been shown (e.g. Wechsler et al. 2001; Bullock et al. 2002) that this can be used to constrain the halo occupation function for LBGs (see Section 6), which in turn provides information on their typical masses and likely evolutionary fate (e.g. Moustakas & Somerville 2002).

The clustering of galaxies, as represented by the two-point correlation function, has been shown to be well approximated by a power law (e.g. Peebles 1980) of the form $\xi(r) = (r/r_{\text{e}})^{-\gamma}$. The angular projection of this also follows a power law of the form $w(\theta) = A_w \theta^{-\beta}$, where $\beta = \gamma - 1$. We calculate the two-point angular correlation function, $\omega(\theta)$, for $i'$-band selected galaxies, using the estimator of Landy & Szalay (1993):

$$\omega(\theta) = 1 + \frac{DD(\theta)}{RR(\theta)}W_1 - 2\frac{DR(\theta)}{RR(\theta)}W_2,$$

where $DD(\theta)$, $RR(\theta)$, and $DR(\theta)$ are the numbers of 'data-data', 'random-random' and 'data-random' pairs, respectively, and $W_1$ and $W_2$ account for the numbers of data and random points ($N_{\text{ran}}$ and $N_{\text{data}}$) used to estimate the correlation function (Roche & Eales 1999). Here,

$$W_1 = \frac{N_{\text{ran}}(N_{\text{ran}} - 1)}{N_{\text{data}}(N_{\text{data}} - 1)},$$

and

$$W_2 = \frac{(N_{\text{ran}} - 1)}{N_{\text{data}}}.$$

In the data we remove bright stars, diffraction spikes, bad columns, etc., and constrain the random sample so that it follows the same geometrical constraints as the data.

The Poisson error for the angular correlation function can be calculated using:

$$\sigma_{\omega(\theta)} = \frac{1 + \omega(\theta)}{\sqrt{DD(\theta)}}$$

However, $\sigma_{\omega(\theta)}$ is probably an underestimate of the actual error in $\omega(\theta)$ when the number of data points used is small (Baugh et al. 1996). In order to obtain a more appropriate

---

Table 6. The surface and space densities for different $i'$-band selection magnitude bins. Surface densities are per half magnitude bin.

| Magnitude range ($i'$) | \(\Sigma\) (arcmin\(^{-2}\)) | \(n_{\Sigma}(\text{h}^{-3}\text{Mpc}^{-3})\) |
|------------------------|-------------------------------|---------------------------------|
| 23.0 – 23.5            | 0.0065 ± 0.0004               | 6.29 ± 5.30 × 10\(^{-6}\)       |
| 23.5 – 24.0            | 0.0165 ± 0.0085               | 1.60 ± 1.10 × 10\(^{-5}\)       |
| 24.0 – 24.5            | 0.0685 ± 0.0101               | 6.63 ± 1.31 × 10\(^{-5}\)       |

---

Figure 8. Normalised fiducial redshift distribution consistent with photometric models (bold solid line corresponding to a Gaussian with \(\bar{z} = 4.0\) and \(\sigma_z = 0.2\)). The other lines show the range of selection functions considered to test the sensitivity of the Limber deprojection to the assumed redshift distribution. The bold short-dashed line shows a ‘tophat’ function with centred on \(\bar{z} = 4.0\) with \(\sigma_z = 0.5\). The thin long dashed lines correspond to Gaussians with \(\bar{z} = 3.5\) and 4.5 with \(\sigma_z = 0.2\). Finally, the thin solid line corresponds to a much wider redshift distribution with \(\sigma_z = 0.4\).

Figure 9. The surface density of colour-colour selected LBGs in the ODT Survey (filled squares). Also shown are data from Ouchi et al. (2001) (open circles), Steidel et al. (1999) (crosses), and data from the Hubble Deep Field, Arnouts et al. (1999) (asterisks). Surface densities are plotted per unit magnitude.
estimate of the errors on \( w(\theta) \), we compute bootstrap errors (Ling et al. 1998).

If a sample contains \( n \) galaxies then a ‘bootstrap’ sample can be created by drawing (with replacement), \( n \) galaxies from the original galaxy sample. This process can be repeated \( N \) times and the correlation function, \( \hat{w}(\theta) \), calculated for each of the \( N \) bootstrap samples (where \( i = 1, 2, 3...N \)). The estimate of the error in \( w(\theta) \) is then given by:

\[
\sigma_{\text{boot}} = \left( \frac{1}{N-1} \sum_{i=1}^{N} \left[ \hat{w}(\theta) - \hat{w}_{\text{obs}}(\theta) \right]^2 \right)^{1/2},
\]

(12)

The computed bootstrap errors are shown in Figures 10 and 11 and are used in what follows.

Due to the fact that we are using a finite solid angle, we correct the estimate of \( \omega(\theta) \) for the integral constraint (Groth & Peeebles 1973; Roche & Eales 1999):

\[
IC = \frac{1}{\Omega} \int \int \omega(\theta_1,\theta_2) \delta \Omega_1 \delta \Omega_2,
\]

(13)

where \( \Omega \) is the solid angle. The integral constraint can be estimated (providing enough random points are used) with \( IC = \Omega \omega \) where \( B \) is given by:

\[
B = \frac{\sum RR(\theta) \theta^{-\beta}}{\sum RR(\theta)}.
\]

(14)

The angular correlation function then becomes,

\[
w(\theta) = w_{\text{obs}}(\theta) + IC = \omega(\theta)^{\theta^{-\beta}}.
\]

(15)

The best fitting parameters \( \omega \) and \( \beta \) can be found by finding the best (\( \chi^2 \) minimisation) fit to the function \( w_{\text{obs}}(\theta) = \omega(\theta)^{\theta^{-\beta} - B} \), for different values of \( \beta \), where \( B \) is recalculated each time. The error on \( \omega \) is computed as the value that gives \( \Delta \chi^2 = 1 \).

Figure 10 shows the angular correlation function for the fainter sample of 66 LBG candidates covering an area where we are confident there is comparable completeness to \( i < 24.5 \). Some 90,000 random objects were used in this calculation. The angular correlation function for the ‘bright’ sample to \( i = 24.0 \) is shown in Figure 11 based on 74 LBG candidates. Here, 250,000 random objects were used to calculate the correlation function. Since the clustering strength of faint galaxies is significantly less than that discussed below for bright LBGs, faint galaxies in the same catalogue could also be used as an effective sample of ‘random’ objects. This provides a good test that there is no remnant structure due to varying completeness in the \( i \) band data. The galaxies to be used as ‘random’ objects were selected to cover the same magnitude range as the LBGs (i.e. 23.0 < \( i < 24.5 \) for the faint sample, and 23.0 < \( i < 24.0 \) for the bright sample). Similar correlation strengths to using a truly random distributed each time. The error on \( \omega \) can be created by drawing (with replacement) \( \Omega \) canes to be used as ‘random’ objects were selected to cover the

\[
\Delta \chi^2 = 1
\]

\[
\beta = 0.8,
\]

\[
\Omega = 15.39
\]

\[
IC = 0.064
\]

Figure 10. The angular correlation function for 66 \( i < 24.5 \)

There is increasing evidence that faint samples of \( I \)-band selected galaxies (and therefore galaxies with a higher median redshift) have a shallower slope, \( \beta \), to the best fitting power law \( w(\theta) = \omega(\theta)^{\theta^{-\beta}} \) than the often quoted \( \beta = 0.8 \) seen in clustering studies of local galaxies (e.g. Brainerd & Smail 1998; Postman et al. 1998; McCracken et al. 2001). In addition, many measurements of LBG clustering also find a best fitting slope that is shallower than 0.8 (e.g. Ouchi et al. 2001; Porciani & Giavalisco 2002), although few of the measurements are accurate enough to test whether or not this is significantly different to the local Universe, and so results are usually quoted with a fit constrained to \( \beta = 0.8 \).

In the ODT data for \( i < 24.5 \) the best fitting parameters (with \( \theta \) in arcsec) are consistent with this (\( \omega = 7.43^{+12.4}_{-5.0} \), \( \beta = 0.63^{+0.24}_{-0.23} \)). However, there are not enough data to place a strong constraint on this slope. Therefore, to be consistent with other measures of LBG clustering in the literature, only results for a constrained slope of \( \beta = 0.8 \) are considered in what follows. However, we note that LBG correlation functions with a shallower slope would have the general effect of increasing estimates of \( r_0 \) (in this case by \( \sim 15\% \)). This is something that will need to be looked into in more detail in the full ODT sample, and in other high quality data sets probing the high redshift Universe.

Confining the slope of the angular correlation function to 0.8, we obtain an amplitude \( \omega \) of 15.39 ± 4.3 arcsec\(^2\) for the faint \( i < 24.5 \) sample. For the brighter sample a best-fitting amplitude of \( \omega = 16.40 \pm 8.6 \) arcsec\(^2\) was calculated. The quoted errors in \( \omega \) correspond to the error on the best fit to the power law \( w(\theta) = \omega(\theta)^{\theta^{-0.8}} \). We make no attempt here to correct the correlation function for contamination, in line with similar studies with similar contamination estimates. However we note that, in the case of maximum contamination our estimates of \( \omega \) could be

2 The technique of \( \chi^2 \) minimisation assumes independent errors. In fact, the errors on \( w(\theta) \) measurements are correlated. This complication is neglected here, but we note that if \( \chi^2 \) is used to test goodness-of-fit, it is likely to be an underestimate.
that describes the cosmology,
\[ g(z) = \frac{H_0}{c} [(1 + z)^2 (1 + \Omega_m z + \Omega_L (1 + z)^{-2} - 1)^{1/2}], \]
and \( F(z) \) is the redshift dependence of \( \xi(r) \).

Since the selection function for LBGs is very narrow (especially as a function of time), the function \( F(z) \) can be removed from the integral. This can be verified by using both linear and non-linear clustering evolution for the function \( F(z) \) over our redshift distribution. We find this gives only negligible changes in \( r_0 \) (c.f. Ouchi et al. 2001). Porciani & Giavalisco 2002. The comoving \( r_0 \) at redshift \( z \) is therefore given by:

\[ r_0(z) = r_0[F(z)]^{1/\gamma}. \]

Using our fiducial redshift distribution and the angular correlation function parameters derived in Section 5.2, we obtain a spatial correlation length (at \( z \sim 4 \)) of \( r_0 = 11.4_0^{+1.7}_{-1.4} h^{-1} \) Mpc for the \( i' < 24.5 \) sample. For the \( i' < 24.0 \) sample we obtain \( r_0 = 11.8_0^{+3.4}_{-2.1} h^{-1} \) Mpc (see Table 7 for a summary of these results). These correlation lengths are considerably greater than other measurements at \( z \sim 4 \) (e.g. Arnouts et al. 1999, 2002; Ouchi et al. 2001) and the implications and context of this are discussed in Section 6.

In order to test the accuracy of these results we vary the \( N(z) \) distribution introduced in Section 4.2 over a reasonable range of values for \( \bar{z} \) and \( \sigma_z \) and also consider a simple top-hat redshift distribution (see Figure 8). We find that the calculated \( r_0 \) is only weakly dependent on the \( \bar{z} \) used, and is only affected at the 10% level, even using a top-hat distribution over 3.5 \( < z < 4.5 \). However, significant broadening of the selection function by increasing \( \sigma_z \) to 0.4 would increase \( r_0 \) by up to 40%. It should also be noted that narrower selection function would lead to smaller values of \( r_0 \). A Gaussian selection function with \( \sigma_z \) reduced to 0.1 would lead to an \( r_0 \) that is \( \sim 20\% \) smaller. If we consider the maximum final contamination given in Table 3 and assume that contaminants are unclustered (see Section 5.1), we find that \( r_0 \) would increase by 15%. Note that our quoted results contain the error derived from the best fitting power law only. In line with other LBG studies, the effects of systematic uncertainties are not considered further.

\[ \sigma_8 = \Omega_m^{1/2} (\Omega_b^2 / \Omega_m) (H_0 / 100 \text{ km s}^{-1} \text{ Mpc}^{-1})^{1/2}. \]

3 If the contaminants are unclustered then \( A_w \) would be reduced by a factor \( (1 - f)^2 \), where \( f \) if the contamination fraction. In the case where contaminants are clustered, and their clustering amplitude is smaller than that for LBGs, the reduction in \( A_w \) would be less.
given physical scale $R$, using the relation between mass-scale and variance. At redshift $z$, the dark-matter variance is given by:

$$\sigma_{dm}(z) = \sigma_{dm}(z = 0) \times D_{lin}(z),$$

(22)

where $D_{lin}(z)$ is the linear growth factor at the redshift of interest; at redshift 4, $D_{lin}(z = 4) = 0.25569$. The $\sigma_i$ is calculated (assuming $\xi$ is described by a power law) as:

$$\sigma^2_i = J_2 \left( \frac{r_0}{r} \right)^\gamma,$$

(23)

where,

$$J_2 = \frac{72}{(3-\gamma)(4-\gamma)(6-\gamma)^2}.$$  

(Peebles 1980). See Somerville et al. (2004) for further details and discussion.

For $i' < 24.5$ we obtain $b = 8.1^{+2.1}_{-1.2}$, and for $i' < 24.0$, $b = 8.4^{+2.0}_{-0.6}$. The clustering and bias results are summarised in Table 4.

6 DISCUSSION

In hierarchical models of structure formation, structure forms by the magnification of initial density fluctuations by gravitational instability. A key feature is that virialised structures (or dark matter haloes) should have clustering properties that differ from that of the overall mass distribution, with more massive haloes being more strongly clustered (e.g. Kaiser 1984). If galaxies and clusters form when baryonic material falls into the potential wells of the dark matter haloes then a correlation between galaxy (and hosting halo) mass and clustering strength (and therefore bias) would be expected.

An important measurement in studies of LBGs has been that of their clustering properties. The strong spatial clustering and surface densities exhibited by LBGs at $z \sim 3$ appears to be consistent with biased galaxy formation, implying an association between LBGs and fairly massive dark matter haloes, even if there are several galaxies per dark matter halo (e.g. Giavalisco et al. 1998; Giavalisco & Dickinson 2001; Somerville et al. 2001; Wechsler et al. 2001; Bullock et al. 2002). The measurement of the clustering properties of $z \sim 4$ LBGs from the ODT survey provides values of $r_0$ and $b$ that are significantly larger than previous measurements of these parameters at this redshift (Ouchi et al. 2001, Arnouts et al. 1999), and of U-band dropouts at $z \sim 3$ (Giavalisco et al. 1998; Arnouts et al. 1999; Giavalisco & Dickinson 2001; Porciani & Giavalisco 2002). However, the data presented here are from a sample that is much brighter than other measurements of the correlation function at $z \sim 4$. We are therefore able, by combining these shallower wide-field data with deeper pencil-beam surveys such as the Hubble and Subaru deep fields, to compare with the luminosity dependent bias detected in the local Universe (Norberg et al. 2002) and at high redshifts (Giavalisco & Dickinson 2001; Foucaud et al. 2002; Ouchi et al. 2004), and test models of biased galaxy formation. Using our definition of bias (Equation 20) we calculate bias parameters for the $z \sim 4$ Subaru deep field clustering results of Ouchi et al. (2001). We obtain $b = 2.6$ for $i' < 25.5$ and $b = 2.2$ for $i' < 26.0$. We also consider the more recent results of Ouchi et al. (2004) who present clustering results for several differently defined LBG samples. The three samples using data up to a given magnitude limit (with $b = 5.3$ for $i' < 24.8$, $b = 3.5$ for $i' < 25.3$, and $b = 2.9$ for $i' < 26.0$) are used here. When these data are considered alongside the data presented in this paper, there appears to be a clear trend between the depth of a sample and LBG bias. At $z \sim 4$, our faintest magnitude limit of $i' \approx 24.5$ corresponds to a rest-frame absolute magnitude of $M_{1700} \approx -20.5$ at $\lambda_{rest} = 1700$ Å.\(^4\) Employing the $z \sim 4$ luminosity function of Steidel et al. (1999), the faintest galaxies in our sample are then $L_{1700} \approx 1.5 L_*$ (the brightest being $L_{1700} \approx 6.1 L_*$), whereas the Ouchi et al. (2001) and Arnouts et al. (1999, 2002) samples are, on the whole, sub-$L_*$. The luminosity/bias results are summarised in Table 4 and are plotted in Figure 12.

One interpretation of luminosity dependent bias could be a tight correlation between dark matter halo mass and star formation rate (i.e. UV luminosity; Giavalisco & Dickinson 2001; Steidel et al. 1998). The observed $i'$-band magnitudes measured here correspond to a rest-frame of $\lambda \sim 1500$ Å. At this wavelength we are measuring the UV luminosity which is a good tracer of the star formation rate in the galaxy. We can therefore infer a link between halo mass and star formation rate. However we emphasise that the rest-frame UV luminosity is more indicative of the instantaneous star formation rate, rather than total underlying light (and therefore stellar mass).

\(^4\) To calculate the appropriate $k$-corrections, we have used the rest-frame UV SED of Shapley et al. 2003.
Summary of correlation function parameters, bias and number densities. The bias is calculated as $b = \sigma_{g}/\sigma_{dm}$ using linear theory and a power spectrum via $n = 1$ and $\sigma_8 = 0.9$.

6.1 The Masses and Environments of Bright $z \sim 4$ LBGs

In Figure 13 we plot bias versus comoving space density for galaxies at $z \sim 4$. The observed space densities are calculated in Section 4.3. For the ODT bright sample of $i' < 24.0$ and the faint sample of $i' < 24.5$, we obtain bias values of 8.4 and 8.1, respectively. The corresponding space densities, calculated using the same selection function used for the correlation function inversion, are $2.23 \times 10^{-5}$ and $8.86 \times 10^{-5} h_{100}^{-3}$ Mpc$^{-3}$. We also show points for the Ouchi et al. (2004) results, using their estimated effective volume and the reported numbers of LBGs for each limiting magnitude (with estimated uncertainties).

The line in Figure 13 depicts the correspondence between linear bias and comoving space density for dark matter halos at $z = 4$ (based on Sheth & Tormen 1999; see also Somerville et al. 2004). Smaller space densities correspond to more rare overdensities, and therefore to higher minimum dark matter halo masses (as shown). This is the relation that ΛCDM predicts that galaxies would follow, if there were only one galaxy in each dark matter halo, which is a useful simplification for checking trends, but not how galaxies tend to exist. In cases where there may be varying numbers of galaxies per halo, particularly likely if these are starbursting galaxies, the ‘halo occupation’ formalism is a useful parameterisation. Here, above some threshold minimum mass, we assume there is a function $N(M > M_{\text{min}}|\alpha, M_1)$ that describes both the internal mass-function slope ($\alpha$), and the mass of a dark matter halo that typically hosts one galaxy ($M_1$; therefore, there may statistically be $M > M_{\text{min}}$ halos that have no resident galaxies). This prescription is found to describe galaxies at both $z \sim 0$ very well (Marinoni & Hudson 2003; van den Bosch, Yang, & Mo 2003; Magliocchetti & Porciani 2003: and $z \sim 3$ (e.g. Wechsler et al. 2002; Bullock et al. 2002; Kravtsov et al. 2004).

A detailed exploration of the occupation statistics of LBGs implied by our measurements is beyond the scope of this paper. It is useful, however, to turn to the one-galaxy-per-halo curve, and note two items. First, the data span a large dynamic range of space densities, and yet follow the same general trend as the haloes. This suggests that the generic $b/n$ correlation predicted by ΛCDM is reflected in the data. Second, the mass-scale of the ODT LBG sample, $M_{\text{min}} \sim 10^{12} h^{-1} M_\odot$, begs the question whether these naturally connect with later galaxy populations known to be in similarly massive environments. In Moustakas & Somerville (2002), the possible clustering evolution between massive galaxy populations at $z \sim 0, 1.2$, and 3 were explored in the context of simple ΛCDM-motivated models. The $z \sim 3$ galaxy population characteristics were drawn from the literature of largely-sub-$L^*$ samples, and were shown to have a natural connection with the lower-redshift ($z \sim 1.2$) populations, which

| Reference          | Sample  | $A_w$ | $r_0$ ($h^{-1}_{100}$ Mpc) | $b$             | $n$ ($h^3$ Mpc$^{-3}$) |
|--------------------|---------|-------|---------------------------|-----------------|-------------------------|
| ODT (this paper)   | $i' < 24.0$ | 16.40 | 11.8$^{+3.1}_{-4.0}$      | 8.4$^{+2.0}_{-1.9}$ | (2.23 ± 0.25) $\times 10^{-5}$ |
| ODT (this paper)   | $i' < 24.5$ | 15.39 | 11.4$^{+1.7}_{-1.9}$      | 8.1$^{+1.2}_{-1.1}$ | (8.86 ± 0.49) $\times 10^{-5}$ |
| Ouchi et al. (2001)| $i' < 25.5$ | 0.97  | 3.2$^{+1.0}_{-1.2}$       | 2.6$^{+0.7}_{-0.9}$ | (1.71 ± 0.07) $\times 10^{-3}$ |
| Ouchi et al. (2001)| $i' < 26.0$ | 0.71  | 2.7$^{+0.5}_{-0.6}$       | 2.2$^{+0.4}_{-0.5}$ | (3.72 ± 0.11) $\times 10^{-3}$ |
| Ouchi et al. (2004)| $i' < 24.8$ | 6.1   | 7.9$^{+2.1}_{-2.7}$       | 5.3$^{+1.8}_{-1.7}$ | (2.2 ± 0.6) $\times 10^{-4}$ |
| Ouchi et al. (2004)| $i' < 25.3$ | 2.6   | 5.1$^{+1.1}_{-1.0}$       | 3.5$^{+0.6}_{-0.7}$ | (9.2 ± 1.1) $\times 10^{-4}$ |
| Ouchi et al. (2004)| $i' < 26.0$ | 1.7   | 4.1$^{+0.2}_{-0.2}$       | 2.9$^{+0.1}_{-0.1}$ | (4.9 ± 0.30) $\times 10^{-3}$ |

Table 7. Summary of correlation function parameters, bias and number densities.
are plausibly connected with the most massive (elliptical-
galaxy-type) environments today. The $z \sim 1.2$ (ERO) popu-
lisation’s linear bias and comoving space density, when ex-
trapolated to $z \sim 4$ (under the ‘constant minimum mass’
model; Moustakas & Somerville 2002) are expected to have $b \approx 8$ and $n \approx 10^{-5} h_{100}^{-3}$ – values remarkably close to
those measured in the super-$L_*$ ODT LBG sample.

6.2 Significance of Results

Thus far the quoted errors on our measured $r_0$ and bias
have only included ‘random’ errors based on the best fit to
the angular correlation function. In Section 5.2 we derived
our redshift distribution based on an analysis of theoretical
colours of high redshift galaxies. We also considered a range
of possible median redshifts and found that this led to a
$\pm 10\%$ uncertainty on the derived value for $r_0$. Combining
this error in quadrature with the measured statistical errors
leads to $r_0 = 11.4^{+2.0}_{-3.9}$ and $r_0 = 11.8^{+3.3}_{-4.5}$. This is a difference
from the results of Ouchi et al. (2001) at the 3.7-$\sigma$ level for
the faint sample and 2.1-$\sigma$ for the bright sample.

In Section 5.2 the possibility of broader and narrower
redshift distributions than the one we assumed was also dis-
cussed, leading to possible increases in $r_0$ of up to 40%,
and decreases in $r_0$ of up to 20%. Using a $+40\%/-20\%$ un-
certainty for the redshift distribution gives values of $r_0 = 11.4^{+2.0}_{-3.9}$ and $r_0 = 11.8^{+3.3}_{-4.5}$ for the faint and bright samples
respectively. This would be enough to reduce the difference
from the Ouchi et al. (2001) results to the 2.7-$\sigma$ and 1.9-$\sigma$
level.

We also noted in Section 5.2 that the effect on contamina-
tion on our LBG sample is likely to dilute the correlation
function, and any correction that might be applied would
lead to an increase in $r_0$, further strengthening any relation-
ship between luminosity and bias.

6.2.1 Cosmic Variance

Since the LBG population is known to be strongly clustered,
it is clear that the number density of objects will vary from
field to field. It is therefore important that a large enough
volume of sky is surveyed so that this ‘cosmic variance’ does
not significantly bias the measured number density of ob-
jects relative to the overall cosmic average. In order to esti-
mate the size of such an effect on this data set we use the
results of Somerville et al. (2003) who compute the variance
of dark matter from linear theory as a function of redshift.

Based on the estimated effective volume at $z \sim 4$ cov-
ered in this survey ($3 \times 10^8$ Mpc$^3$, assuming $h = 0.7$), the variance in the mean dark matter density is estimated to be
15% (see Figure 3b in Somerville et al. 2004). How cosmic variance relates to an uncertainty in number density of a
population depends on how biased that population is rela-
tive to the overall dark matter distribution. Assuming the
bias measured in Section 5.2 is correct, then the uncertainty
in the number density of LBGs due to cosmic variance can
be estimated as $\sigma_v = 8.1 \times 0.15 = 1.2$. Therefore, in Figure
13 there is an additional uncertainty in the estimated space
density due to the sample size (volume) and cosmic variance
associated with this.

Could fluctuations in number density caused by cos-
mic variance produce the observed difference in clustering
strength between the ODT and fainter samples? This is diff-
ticult to test since estimates of the size of cosmic variance
effects from linear theory require prior knowledge of the rela-
tionship between the galaxy population being studied and
the underlying dark matter distribution (i.e. bias). However,
if we start with the null hypothesis that the intrinsic bias
of the ODT LBG sample is actually the same as that mea-
sured by Ouchi et al. (2001), then the uncertainty in number
density due to cosmic variance, $\sigma_v = 2.6 \times 0.15 = 0.39$
(following Somerville et al. 2003). If we have underestimated
the intrinsic number density due to cosmic variance, and
assume that $\xi \propto 1/(n^2)$, then the ‘true’ number density
could indeed be larger, and the correlation length (and hence bias) could be smaller. Taking $\sigma_v = 0.39$, and assum-
ing a 2-$\sigma$ fluctuation, implies an upper limit on the
number density of $1.58 \times 10^{-4} h_{100}^3$ Mpc$^{-3}$. If this corre-
lates to the Ouchi et al. (2001) correlation length of
$r_0 = 3.2 h_{100}^4$ Mpc, then our measured value for the number
density $(8.86 \times 10^{-5} h_{100}^3$ Mpc$^{-3})$ would scale to 6.1 $h_{100}^4$
Mpc which is inconsistent with our measured values (in fact
a 3-$\sigma$ fluctuation in number density is required to scale
the Ouchi et al. (2001) value to $11.4 h_{100}^4$ Mpc). Variations
in number density due to cosmic variance are too small to ex-
plain the difference in clustering strength between the ODT
and fainter samples. However, it is clear that wide field sur-
veys at least as large as the ODT are required to measure
the clustering properties of the brightest objects. We also
note that the independent results of Ouchi et al. (2004) are
consistent with the trend of increasing clustering strength
with brighter magnitudes at $z \sim 4$.

6.3 Small Scale Clustering and Close Pairs

In addition to a luminosity dependent bias,
Porciani & Giavalisco (2002) provide evidence from a
fairly bright sample of $z \sim 3$ LBGs that there is also a
significant scale-dependent bias. In their data set there
appears to be a lack of power in the angular correlation
function (and therefore a lower bias) on scales less than
30 arcsec. Bullock et al. (2002) also demonstrate (where
redshifts are available) how close pair statistics can be used
within the halo occupation function formalism to place
constraints on different models for the occupation function.
Porciani & Giavalisco (2002) interpret the ‘break’ in their
correlation function as evidence that the dark matter haloes
have a fairly large size and mass, which is more consistent
with one-galaxy-per-halo occupation functions. However it
should be noted that our analysis (and that of most other
LBG clustering studies) has assumed a simple power law
function (and therefore a lower bias) on scales less than
$3 LBGs that there is also a

\[ \frac{\sigma_v}{\sigma_c} \approx 1 \] (see Figure 3b in Somerville et al. 2004). How cosmic variance relates to an uncertainty in number density of a
population depends on how biased that population is rela-
tive to the overall dark matter distribution. Assuming the
bias measured in Section 5.2 is correct, then the uncertainty
in the number density of LBGs due to cosmic variance can
be estimated as $\sigma_v = 8.1 \times 0.15 = 1.2$. Therefore, in Figure
13 there is an additional uncertainty in the estimated space
density due to the sample size (volume) and cosmic variance
associated with this.

Could fluctuations in number density caused by cos-
mic variance produce the observed difference in clustering
strength between the ODT and fainter samples? This is diff-
ticult to test since estimates of the size of cosmic variance
effects from linear theory require prior knowledge of the rela-
tionship between the galaxy population being studied and
the underlying dark matter distribution (i.e. bias). However,
if we start with the null hypothesis that the intrinsic bias
of the ODT LBG sample is actually the same as that mea-
sured by Ouchi et al. (2001), then the uncertainty in number
density due to cosmic variance, $\sigma_v = 2.6 \times 0.15 = 0.39$
(following Somerville et al. 2003). If we have underestimated
the intrinsic number density due to cosmic variance, and
assume that $\xi \propto 1/(n^2)$, then the ‘true’ number density
could indeed be larger, and the correlation length (and hence bias) could be smaller. Taking $\sigma_v = 0.39$, and assum-
ing a 2-$\sigma$ fluctuation, implies an upper limit on the
number density of $1.58 \times 10^{-4} h_{100}^3$ Mpc$^{-3}$. If this corre-
lates to the Ouchi et al. (2001) correlation length of
$r_0 = 3.2 h_{100}^4$ Mpc, then our measured value for the number
density $(8.86 \times 10^{-5} h_{100}^3$ Mpc$^{-3})$ would scale to 6.1 $h_{100}^4$
Mpc which is inconsistent with our measured values (in fact
a 3-$\sigma$ fluctuation in number density is required to scale
the Ouchi et al. (2001) value to $11.4 h_{100}^4$ Mpc). Variations
in number density due to cosmic variance are too small to ex-
plain the difference in clustering strength between the ODT
and fainter samples. However, it is clear that wide field sur-
veys at least as large as the ODT are required to measure
the clustering properties of the brightest objects. We also
note that the independent results of Ouchi et al. (2004) are
consistent with the trend of increasing clustering strength
with brighter magnitudes at $z \sim 4$.

5 This approximation ($\xi \propto 1/(n^2)$) assumes that Gaussian statis-
tics apply, which is not the case here. A full calculation of the ef-
effects of cosmic variance requires knowledge of higher order cluster-
ing statistics. Simulations by Foucaud et al. (2003) suggest that
for a similar bright sample but at $z \sim 3$, the size of the cosmic
error is likely to be smaller than the measured Poisson errors.
However, this rough calculation provides a useful measure of the
potential size of the ‘cosmic error’.
would lead to over-estimates of $r_0$ for LBGs). The models of Hamana et al. (2004) indicate that the observed angular correlation function is well fitted by a two-component power law with a steep component dominating on small scales, although Ouchi et al. (2004) fit the same data with single component model with a relatively steep ($\beta = 0.9$) slope.

In the ODT data presented here we find no close pairs on scales less than 10 arcsec in the $i' < 24.5$ sample and none less than 40 arcsec in the brighter $i' < 24.0$ sample. Unfortunately, since only one or less pairs would be required to fit the best-fitting power law on these scales, it is not possible to determine whether or not this constitutes evidence to support the results of Porciani & Giavalisco (2002), or indeed to determine whether a steeper slope is more appropriate on small scales. However an analysis of the full ODT survey should yield a good measurement of the small-scale component model with a relatively steep ($\beta = 0.9$) slope.

The main results presented here can be summarised as follows:

- The clustering of LBGs at $z \sim 4$ is well approximated by a power law $w(\theta) = A_w \theta^{-\beta}$. Fixing the slope to that of local galaxies ($\beta = 0.8$), provides a good fit to the data with $A_w = 15.39$ arcsec$^{-0.8}$ for $i' < 24.5$ and $A_w = 16.40$ arcsec$^{-0.8}$ for $i' < 24.0$. However we note that there is evidence to suggest that $\beta = 0.8$ may not be a valid assumption to make at high redshift, and a shallower slope may be more appropriate.
- Using a reasonable fiducial redshift distribution to characterise the selection function for LBGs, the angular correlation function can be deprojected to obtain the spatial correlation length, $r_0$. For our fainter sample ($i' < 24.5$) we obtain $r_0 = 11.4^{+1.7}_{-1.9} h^{-1}_{100}$ Mpc. Using a slightly brighter sample ($i' < 24.0$) we obtain a similar correlation length of $r_0 = 11.8^{+3.1}_{-4.0} h^{-1}_{100}$ Mpc. Comparing these results to the clustering properties of dark matter, we obtain linear bias values of $8.1^{+2.4}_{-1.2}$ and $8.4^{+2.6}_{-2.4}$ respectively.
- When compared with fainter surveys the bias and correlation lengths seen in the ODT are clearly significantly larger. We interpret this as evidence for a luminosity dependent bias for LBGs, as predicted by some semi-analytic models. The ODT bias values are shown to be consistent for a simple model using a galaxy occupation function describing one observable galaxy per dark matter halo. Bright (super$-L_*$) LBGs seem to be more biased tracers of mass than fainter (sub$-L_*$) ones, suggesting a relationship between halo mass and instantaneous star formation rate.
- The population of sub$-L_*$ LBGs are unlikely to be the progenitors of massive galaxies at $z \sim 1$ and $z \sim 0$. However, the extremely bright, super$-L_*$ population presented in this paper have biases, number densities and halo masses ($M_{\text{min}} \sim \text{few} \times 10^{12} h^{-1} M_\odot$) that are consistent, in a simple model, with them being potential progenitors of the most massive galaxies.

The data presented here are only a small sample of the full ODT survey. With an extended sample containing $> 1000$ LBGs over a much wider area it should be possible to place stronger constraints on the clustering properties of this bright sample of high redshift galaxies, and address issues such as their scale dependent bias. In addition, other surveys currently underway such as the NDWFS (Jannuzi & Dev 1997), GOODS (Dickinson et al. 2003), the VIRMOS-VLT deep survey (Le Fevre et al. 1998), the CFHT Legacy survey$^5$, SXDS (Kodama et al. 2004), and COSMOS$^7$, should provide good measurements of LBG clustering probing (when combined) a large dynamic range in luminosity and redshift. This should allow tighter constraints on parameters such as the galaxy occupation function, and the scale and luminosity dependent bias for LBGs; thus providing a better understanding of the relationship between LBGs, other high-$z$ populations, and galaxies today.

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$^5$ http://www.cfht.hawaii.edu/Science/CFHTLS
$^7$ http://www.astro.caltech.edu/~cosmos

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