Verifying the identity of high-redshift massive galaxies through the clustering of lower mass galaxies around them

Joseph A. Muñoz* and Abraham Loeb*

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS 10, Cambridge, MA 02138, USA

Accepted 2008 January 16. Received 2008 January 9; in original form 2007 November 3

ABSTRACT

Massive high-redshift galaxies form in overdense regions where the probability of forming other galaxies is also strongly enhanced. Given an observed flux of a galaxy, the inferred mass of its host halo tends to be larger as its inferred redshift increases. As the mass and redshift of a galaxy halo increase, the expected clustering of other galaxies around it gets stronger. It is therefore possible to verify the high-redshift identity of a galaxy (prior to an unambiguous spectral identification) from the clustering of other galaxies around it. We illustrate this method for the massive galaxy suggested by Mobasher et al. to be at redshift \( z \sim 6.5 \). If this galaxy were to exist at \( z \sim 6.5 \), there should have been a mean of \( \sim 10 \) galaxies larger than a hundredth of its mass and having \( z \)-band magnitudes less than \( \sim 22 \) detected as i-drops in the Hubble Ultra Deep Field (HUDF). We calculate an approximate probability distribution for neighbour galaxies and determine that there is less than a \( \sim 0.3 \) per cent chance of detecting no massive neighbour galaxies. The lack of other massive \( z \sim 6.5 \) galaxies in the HUDF image argues that the Mobasher et al. galaxy is instead a low-redshift interloper. We generalize our results to other galaxy masses and redshifts.

Key words: galaxies: high-redshift – cosmology: theory.

1 INTRODUCTION

The purported detection of a very massive galaxy, Hubble Ultra Deep Field-JD2 (HUDF-JD2), at a redshift of \( z \sim 6.5 \) by Mobasher, Dickinson & Ferguson (2005) provides a critical test for the standard paradigm of galaxy formation in a cold dark matter (ΛCDM) cosmology. However, the lack of an unambiguous spectral identification allows this galaxy to be a \( z \sim 2 \) interloper in which obscuration by dust mimics the Lyman break (Chary et al. 2007; Dunlop, Cirasuolo & McLure 2007). If the galaxy is at \( z \sim 6.5 \), the estimated mass of the halo containing this galaxy is \( M_{\text{Halo}} \sim 2 \times 10^{13} M_\odot \) for a reasonable star formation efficiency, \( \epsilon_{\text{SF}} \), of 10 per cent. In the concordance cosmological model, the expected number of such galaxies in the HUDF field-of-view is less than \( 10^{-6} \) (Barkana & Loeb 2006). Since the expected probability of finding such a galaxy in the HUDF is extremely low, its redshift identification is of great importance for testing the standard cosmological model.

Here we point out that, despite the low average abundance of galaxies like JD2 (due to its large mass and high redshift), such a galaxy cannot exist alone. The large-scale overdensity implied by its existence naturally results in neighbouring haloes over and above what would be expected from random fluctuations in the average galaxy population. The surrounding overdense region behaves as if it is part of a closed universe, in which the formation of all galaxies occurs earlier. We approach this problem analytically in this paper. In addition to the deeper fundamental understanding gained from such a treatment, the extreme rarity of objects like JD2 make a statistical analysis using numerical simulations difficult. In Section 2, we show how the excursion set formalism can be used to calculate an approximate probability distribution for the number of neighbours around massive galaxies. We then calculate, in particular, the expected clustering of bright galaxies around the Mobasher et al. (2005) galaxy in Section 3, and explore the dependence of our results on the star formation efficiency, duty cycle and power-spectrum normalization in Section 4. In Section 5, we generalize these results to other halo masses and redshifts. Finally, Section 6 summarizes our main conclusions.

Unless otherwise noted, we assume a flat, ΛCDM model for the universe with the Wilkinson Microwave Anisotropy Probe 3 (WMAP3) cosmological parameters (Spergel, Bean & Döré 2007).

2 METHOD

We assume the simple model for Lyman-break galaxies (LBGs) considered by Stark, Loeb & Ellis (2007), which associates LBGs with merger-activated star formation in dark matter haloes and includes suppression of the star formation efficiency in low-mass haloes by supernova feedback. In the model, the star formation duty cycle, \( \epsilon_{\text{DC}} \), gives the fraction of haloes that contain active star formation.
This fraction has recently been calibrated by the measured luminosity function of LBGs at \( z \sim 6 \) to a best-fitting value with \( 1 - \sigma \) errors of \( \epsilon_{\text{DC}} = 0.25^{+0.43}_{-0.09} \) (Stark et al. 2007). Here we adopt a conservative value of \( \epsilon_{\text{DC}} = 0.14 \), in accordance with our assumed star formation efficiency of \( f_s = 10 \) percent (which matches the fraction of \( \Omega_b \) in stars today). The remaining fraction, \( 1 - \epsilon_{\text{DC}} \), of haloes at \( z \sim 6 \) will not be detected as i-dropout LBGs and may include a population of post-starburst galaxies similar to JD2 itself. For our calculations, we assume no variation of the duty cycle over the redshift range of the selection function of the HUDF.

Haloes with active star formation do not constitute a fair sample of the total halo population. Scannapieco & Thacker (2003) show that these haloes have undergone substantial accretion in their recent past giving them an extra ‘temporal’ bias. While the numerical simulations by Scannapieco & Thacker were done at \( z = 3 \), there is, as yet, no analytical method to predict this extra bias at higher redshift. Thus, our calculations for the number of neighbouring LBGs around massive galaxies at high redshift are lower limits that could be modified in the future with a better understanding of the evolution of the ‘temporal’ bias with mass and redshift.

According to the excursion set prescription (Zentner 2007), if the linear density fluctuations in the universe are extrapolated to their values today and smoothed on a comoving scale \( R \), a point whose overdensity exceeds a critical value of \( \delta_c(z) \approx 1.686 D(z) = 0 / D(z) \), where \( D(z) \) is the linear growth factor at redshift \( z \), belongs to a collapsed object with a mass \( M = (4/3) \pi \rho_c R^3 \) if \( R \) is the largest scale for which the criterion is met, where \( \rho_c \) is the critical density of the universe today. The critical value of the overdensity, extrapolated to today from \( z = 6.5 \), is \( \delta_c(z) = (6.5)^{3} \sim 9.6 \). For a Gaussian random field of initial density perturbations, as indicated by WMAP3 measurements of cosmic microwave background (Spergel et al. 2007), the probability distribution of the extrapolated and smoothed overdensity, \( \delta_R \), is also a Gaussian:

\[
Q_0(\delta_R, S(R)) d\delta_R = \frac{1}{\sqrt{2\pi} S(R)} \exp\left(\frac{-\delta_R^2}{2 S^2(R)}\right) d\delta_R, \tag{1}
\]

with zero mean and a variance given by

\[
S(R) = \int_0^{k_{\text{max}}} \frac{dk}{2\pi^2} k^2 P(k), \tag{2}
\]

where \( P(k) \) is the linear power spectrum of density fluctuations today as a function of wavenumber \( k \), and \( k_{\text{max}} = 1/R \). Since equation (2) is a monotonically decreasing function of \( R \) (or \( M \)), the smoothing scale can be uniquely specified by the variance of the overdensity field smoothed on that scale. The critical threshold for collapse introduces a small correction to the probability distribution such that the distribution of \( \delta_R \) becomes

\[
Q(\delta_R, S(R)) = Q_0(\delta_R, S_R) - Q_0(2 \delta_c - \delta_R, S_R). \tag{3}
\]

The conditional probability distribution of \( \delta_1 \) on a scale specified by \( S_1 \) given a value of \( \delta \) on a larger scale specified by \( S_2 < S_1 \) is

\[
Q(\delta_1, S_1 | \delta, S_2) = Q(\delta_1 - \delta, S_1 - S_2). \tag{4}
\]

Using Bayes theorem, the conditional probability of \( \delta_2 \) on a scale \( S_2 \) given \( S_1 \) on a smaller scale specified by \( S_1 > S_2 \) is

\[
Q(\delta_2, S_2 | \delta_1, S_1) d\delta_2 \propto Q(\delta_1, S_1 | \delta, S_2) Q(\delta_2, S_2) d\delta_2, \tag{5}
\]

with a constant of proportionality such that the integral of equation (5) is unity. Setting \( \delta_1 = \delta_c(z) \) and \( S_1 = S(M_1) \), where \( M_1 \) is the host halo mass of a detected massive galaxy, gives the probability distribution of \( \delta_{\text{obs}} \) on any comoving scale \( R > R_1 \), due to the presence of that galaxy, where \( R_1 \) is the radius corresponding to \( M_1 \).

However, the excursion set formalism calculates the collapse of objects (a non-linear effect) by considering the behaviour of the linear overdensity field extrapolated to the present day. This method functions entirely in Lagrangian coordinates (which move with the flow) and does not take into account how the overdensity field changes in the quasi-linear regime. Obviously, when a region collapses, matter is pulled in from the surrounding region to fill the void. Thus, if we assume the existence of JD2 at \( z = 6.5 \), the material in the rest of the HUDF at that redshift would have started outside the region earlier in the universe’s history.

We denote the Lagrangian radius of a region as \( R_L \). Early in the history of the universe, before the region begins to collapse, this radius is equal to the radius of the region in Eulerian coordinates (which do not move with the flow). As the region collapses, the Eulerian radius shrinks, while \( R_L \) remains unchanged. We denote the final Eulerian radius of the region at the redshift at which it is observed as \( R_E \).

The extent of the collapse depends on the magnitude of the overdensity in the presence of the massive galaxy whose probability distribution we have just calculated in Lagrangian coordinates. The more overdense the region, the larger it would have to be initially to collapse to the same value of \( R_E \). Similarly, a lower value of the overdensity would mean that the material inside \( R_E \) came from a relatively smaller Lagrangian size. We would like a mapping, then, between the comoving Eulerian size of a viewed region (such as the HUDF), and the comoving Lagrangian size of the region from where the same material originated in the early universe. This can be obtained via the spherical collapse model (Mo & White 1996).

A spherically symmetric perturbation of Lagrangian radius \( R_L \) and overdensity \( \delta_L > 0 \) collapses to a sphere of comoving Eulerian size \( R_E \) at redshift \( z \) given by

\[
R_E = \frac{3}{10} \frac{1 - \cos \theta}{\delta_L} \frac{D(z = 0)}{D(z)} R_L, \tag{6}
\]

\[
\frac{1}{1 + z} = \frac{3 \times 6^{2/3} (\theta - \sin \theta)^2}{20 \delta_L}. \tag{7}
\]

For a fixed value of \( R_E \), there is an one-to-one relationship between \( R_L \) and the value of \( \delta_L \) that collapses \( R_L \) to \( R_E \).

In the presence of a massive galaxy, the probability distribution of \( \delta \) (in the Lagrangian sphere that collapsed to \( R_E \)) can be computed by considering the possible histories of the region \( R_E \) having collapsed from different possible \( R_L \)'s weighted by the probability of the corresponding value of \( \delta_L \) in each \( R_L \). These weights are given by equation (5). The resulting probability distribution of \( \delta \) (dropping the subscript \( L \) ‘seen’ in a fixed \( R_E \) can be expressed generally as

\[
\frac{dP(\delta | M_1)}{d\delta} \propto Q(\delta, R_1(\delta, R_1, \Delta R)) | \delta_1(z), R(M_1) \}, \tag{8}
\]

where again the constant of proportionality is set so that \( \int [dP(\delta | M_1)/d\delta] d\delta = 1 \).

Now that we know the distribution of overdensities in which the massive galaxy sits, we can easily calculate the expected number of neighbour galaxies seen in \( R_E \) in the presence of each value for the overdensity, \( \bar{N}(\delta | M_1) \), and thus, the probability distribution of \( \bar{N} \), Barkana & Loeb (2004) calculate the mass function of objects in a region of fixed overdensity by combining the Sheth–Tormen and Press–Schechter prescriptions in the regimes for which each best-fitting results from numerical simulations. Given the relationship between \( \delta \) and \( R_L \) for a given \( R_E \), the overdensity determines the
Lagrangian scale size. We find
\[ N(\delta|M_1) = [V(\delta) - V(M_1)] \epsilon_{\text{DC}} \int_{m_{\text{min}}}^{m_{\text{max}}} \frac{dn_{\text{halo}}}{dm}(m, \delta) \, dm, \]  
(9)
\[ \frac{dn_{\text{halo}}}{dm}(m, \delta) = \frac{dn_{\text{ST}}}{dm}(m, \delta) \int dS \delta \left[ \delta_0(\delta), S(m) \right] S \, dS \]  
(10)
where \(dn_{\text{ST}}/dm\) is the Sheth–Tormen mass function, \(V(\delta)\) is the volume enclosed by the Lagrangian radius specified by \(\delta\) and \(\int dS \delta \left[ \delta_0(\delta), S(m) \right] S \, dS\) is the mass fraction at \(\delta\) contained in haloes with mass in the range corresponding to \((S, S + dS)\). The mass limit \(m_{\text{max}}\) is the mass enclosed by a sphere of today’s critical density with radius \(R_c\), corresponding to \(\delta\). We ignore the probability that \(R_c\), while containing an overdensity \(\delta < \delta_c(\delta)\), might be part of a larger collapsed region with \(\delta > \delta_c(\delta)\). This is a good assumption given the unlikely occurrence of \(\delta = \delta_c(\delta)\) on the scale of \(M_1\) in the first place.

The resulting probability distribution of \(N\), due to cosmic variance, is given by
\[ P(N | M_1) = \sum_{N=0}^{\infty} \hat{P}(\hat{N} | M_1) \cdot P_{\text{Poisson}}(N, \hat{N}), \]  
(13)
where
\[ P_{\text{Poisson}}(k, \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}, \]
\[ \hat{P}(\hat{N} = 0 | M_1) = \int_0^{0.5} \frac{P(N | M_1)}{dN} \, dN, \]
and for \(\hat{N} > 0,\)
\[ \hat{P}(\hat{N} | M_1) = \int_{N-0.5}^{N+0.5} \frac{P(N' | M_1)}{dN'} \, dN'. \]  
(14)

Equation (13) can be compared to galaxy counts in surveys. In particular, if no galaxies in haloes above some minimum mass, \(m_{\text{min}}\), are seen as neighbours to another galaxy in a halo of mass \(M_1\), then the quantity \(1 - P(N = 0 | M_1)\) is approximately the confidence by which we can rule out either the existence of a halo of mass \(M_1\) or the cosmological model.

3 HUFD-JD2

We show results for neighbour i-dropouts around JD2 in the HUDF. If JD2 is indeed a massive galaxy at \(z \sim 6.5\), then there should be many massive galaxies visible around it. Fig. 1 shows the distribution of \(\delta\) given by equation (8) inside the Lagrangian patch that collapses to an angular Eulerian size of \(\sim 115\) arcsec, enclosing an area on the sky roughly equivalent to the HUDF field-of-view. This angular scale corresponds to a comoving size of \(\sim 4.7\) Mpc at \(z = 6.5\), which assuming an extrapolated overdensity of \(\delta = 6.5\), encloses within a spherical radius a mass of \(\sim 10^{14} M_{\odot}\). Also shown are the expected number of neighbours inside that radius, given each value of the overdensity, and the resulting probability distribution of the number of neighbours that includes both cosmic variance and Poisson fluctuations.

While the HUDF should be sensitive to LBGs in hosts as small as \(\sim 2 \times 10^{10} M_{\odot}\), the number of random galaxies expected in such hosts without correlations from JD2 is comparable to the number of excess neighbours that result from these correlations. This creates some ambiguity in detecting the excess over the background. On the other hand, while the mean number of uncorrelated LBGs in haloes as large as \(\sim 2 \times 10^{12} M_{\odot}\) is orders of magnitude smaller than the excess due to JD2, the probability of detecting no such neighbour is not small enough for a lack of a detection to be meaningful.

Thus, we consider neighbour LBGs in haloes with masses above \(\sim 2 \times 10^{11} M_{\odot}\). For a duty cycle \(\epsilon_{\text{DC}} = 0.14\) and star formation efficiency \(f_* = 0.1\), these galaxies have luminosities at 1500 above \(\sim 2 \times 10^{39} \text{erg s}^{-1} \text{Hz}^{-1}\) or z-band magnitudes at \(z \sim 6.5\) less than \(\sim 25\). The mean abundance of such galaxies in the absence of JD2 is much less than unity, and indeed, no such objects have been detected in the HUDF (Bouwens et al. 2006, 2007). Fig. 1 shows that there should be a mean of \(\sim 10\) very bright i-dropout LBGs in hosts with masses larger than within an angular Lagrangian radius of \(\sim 175\) arcsec of JD2, where this is a lower limit due to the fact that LBGs should be more clustered than haloes (Scannapieco & Thacker 2003). The probability, given by equation (13), of detecting no such galaxies in this region is \(P(N = 0 | M_{\text{JD2}}) \sim 3 \times 10^{-4}\). Thus, we can rule out JD2 at redshift \(z \sim 6.5\) with 99.7 per cent confidence. Integrating the distribution, we find a less than a 5 per cent chance of detecting fewer than three very bright neighbour galaxies. Either JD2 is at \(z \sim 2\), as allowed by spectral fits, or there is a problem with our assumed cosmological model.

Figure 1. The upper panel shows the probability distribution of the overdensity \(\delta\) (extrapolated to \(z = 0\)) due to cosmic variance (equation 8) in a spherical region that collapsed to the size of the HUDF assuming the existence of a \(2 \times 10^{13} M_{\odot}\) halo containing JD2 at \(z = 6.5\). The central panel shows, for each value of the overdensity, the resulting number of LBGs in haloes with mass above \(2 \times 10^{11} M_{\odot}\) expected in this region. The final probability distribution of the number of LBGs in the region above \(2 \times 10^{11} M_{\odot}\) is plotted in the bottom panel, taking into account both cosmic variance and Poisson fluctuations.
4 PARAMETER DEPENDENCE

So far, we have assumed a star formation efficiency of \( f_\star = 10 \) per cent, a duty cycle of \( \epsilon_{DC} = 0.14 \) and WMAP3 cosmological parameters with \( \sigma_8 = 0.776 \). We now explore how our results depend on these parameters.

4.1 \( \epsilon_{DC} \) and \( f_\star \)

Given a stellar mass of \( 2 \times 10^{12} \, M_\odot \) for JD2 (Barkana & Loeb 2006), changes in the star formation efficiency will affect the assumed host halo mass. More efficient star formation will, therefore, result in fewer neighbour haloes due to the lower corresponding halo mass. Meanwhile, changes in the duty cycle will affect the fraction of such haloes that are seen as i-dropouts. Yet, these two parameters are not constrained independently. Fig. 4 of Stark et al. (2007) shows very narrow likelihood contours in log-parameter-space. As a rough approximation, then, we assume that the range allowed by the luminosity function fitting spans a power-law relationship between the star formation efficiency and the duty cycle. Using the best-fitting parameter values and the extremes of the \( 1 - \sigma \) contour, we fit the dependence with a least-squares regression (in log-space) and find a relationship given by

\[
f_\star = A \epsilon_{DC}^{\beta},
\]

where \( A = 0.264 \) and \( \beta = 0.378 \).

The mean number of neighbour i-dropouts to JD2 in the HUDF with host halo masses greater than 0.01 \( M_\odot \), denoted \( \langle N \rangle \), is plotted in Fig. 2 as a function of \( \epsilon_{DC} \). Also shown is the effect on the probability of detecting no such galaxies, given by setting \( N = 0 \) in equation (13). As shown, the effect of varying parameters on \( \langle N \rangle \) is only modest. When considering the range of \( 1 - \sigma \) errors on \( \epsilon_{DC} \), \( \langle N \rangle \) varies by only a factor of \( \sim 2 \). The correlation between the star formation efficiency and the duty cycle given by equation (15), causes these parameters to moderate each other’s effect on the expected number of neighbours. While the value of \( P(N = 0) \) varies more significantly, our choice of parameters throughout the rest of the paper gives conservative values for both \( \langle N \rangle \) and \( P(N = 0) \). The best-fitting value of \( \epsilon_{DC} = 0.25 \) derived by Stark et al. (2007) results in an even smaller probability of detecting no bright neighbour dropouts if JD2 is at \( z = 6.5 \).

4.2 \( \sigma_8 \)

The high overdensity in the region surrounding a massive galaxy at high redshift results from the large density fluctuation required to produce such a galaxy. If the overdensity must reach \( \delta_c(z) \) on the scale corresponding to the size of the galaxy, then on a smoothing scale only a little larger, the overdensity could not have been very low, since the contribution from the intervening scales is a Gaussian about zero with a standard deviation much less than \( \delta_c(z) \). However, varying the normalization of the matter power spectrum will change the standard deviation of this Gaussian contribution. Reducing the value of \( \sigma_8 \) will decrease the contribution from these intervening scales and cause the overdensity around massive galaxies to be larger. This will result in more neighbouring galaxies on average and a lower likelihood of detecting none. Conversely, increasing \( \sigma_8 \) will boost the possible contribution from intervening scales, shift the probability distribution of \( \delta \) in regions around massive, high-redshift galaxies toward lower values and result in lower average number of neighbours and a greater chance of detecting none.

We explore the dependence of \( \langle N \rangle \) and \( P(N = 0) \) on \( \sigma_8 \) quantitatively in Fig. 3. The behaviour is just as expected. The dependence

\[ \sigma_8 \]

\[ \langle N \rangle \]

\[ P(N = 0) \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 0.6 \]

\[ 0.7 \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]
is relatively strong given the wide range of proposed values for $\sigma_8$. However, $P(N = 0)$ reaches only $\sim 1$ per cent at $\sigma_8 = 0.9$.

5 POTENTIAL FUTURE DETECTIONS

As new surveys continue to probe for even larger galaxies at even higher redshifts (McLure et al. 2006; Rodighiero et al. 2007; Wiklind et al. 2007), it is important to generalize our results to potential future detections of other massive, high-redshift galaxies in the future. We again assume ($e_{\text{DC}}, f_r, \sigma_8) = (0.14, 0.1, 0.776)$ and calculate the expected number of neighbours as for JD2 but now allowing the mass, $M_1$, and redshift, $z_1$, of the halo hosting the detected galaxy to vary.

Fig. 4 shows the mean number of neighbour LBGs, $\langle N \rangle$, with host halo mass $M_2 > 0.01 \times M_1$ that are within an angular Eulerian separation $\theta = 115$ arcsec from a central galaxy with a host halo mass of $M_1$ situated at a fixed $z_1$ as a function of $M_1$. While the uncorrelated, average abundance of lower mass haloes is larger than that of higher mass haloes, the plot demonstrates that the average number of neighbours begins to increase as a function of $M_1$, for $z_1 = 6.5$ and $8$ above $M_1 \sim 5 \times 10^{12} M_\odot$ due to the non-linear increase in halo clustering with mass. Below this value, the increasing uncorrelated abundance of objects with lower mass causes the number of neighbours to increase with decreasing $M_1$. At $z_1 = 5$, $\langle N \rangle$ decreases as $M_1$ increases in the entire range considered. The cumulative effects of even a very massive halo are dominated by the uncorrelated behaviour at this redshift. The mean number of neighbour LBGs within 115 arcsec is greater than unity for all values of $M_1$ and $z_1$ considered.

The probability of detecting no such neighbours, $P(N = 0)$, is also plotted in Fig. 4. Its dependence on $M_1$ is as expected: $P(N = 0)$ increases as $\langle N \rangle$ decreases.

In Fig. 5, $\langle N \rangle$ and $P(N = 0)$ are plotted as functions of $z_1$ at fixed $M_1$ and $\theta = 115$ arcsec. While the plots of $\langle N \rangle$ and $P(N = 0)$ increase and decrease, respectively, with increasing $z_1$ for $M_1 = 10^{13}$ and $2 \times 10^{13} M_\odot$ due to increased clustering with the detected halo, this is not indicated for $M_1 = 2 \times 10^{12} M_\odot$. As shown in Fig. 4, $d(N)/dM_1 < 0$ at $M_1 = 2 \times 10^{12} M_\odot$ for all values of $z_1$ considered indicating that clustering is less important for these haloes and their neighbours. This is also seen in the larger values of $\langle N \rangle$ for $M_1 = 2 \times 10^{12} M_\odot$ compared to $10^{13} M_\odot$. The increase is due to an uncorrelated population of haloes with mass $2 \times 10^{10} < M_* < 10^{11} M_\odot$. For each set of parameters, a higher value $\langle N \rangle$ corresponds to a lower value of $P(N = 0)$, as expected.

6 DISCUSSION

We have presented a clear signature for the existence of a massive galaxy at high redshift. Because of large correlations among massive haloes at high redshifts, once such an object is found, it is unlikely to be alone. On the contrary, the more massive the halo and the higher its redshift, the greater the number of neighbours it has. This signature is helpful in situations where only photometric data is available or when the spectroscopic redshift identification is ambiguous. For a galaxy of a given observed flux, the inferred halo mass increases as its suggested redshift increases. It therefore becomes easier to rule out a higher redshift hypothesis, using dropout techniques to locate the neighbouring LBGs that are expected at a similar redshift.

We derived a probability distribution for the number of neighbours around a massive galaxy at high redshift, which led to calculations of the mean number of such neighbours and the probability of detecting no such haloes.

In the case of JD2, the number of neighbour galaxies observed in this way can distinguish between the $z \sim 6.5$ interpretation ofMobasher et al. (2005) and that of a galaxy at $z \sim 2$ (Chary et al. 2007; Dunlop et al. 2007). If at $z = 6.5$, the mean number of excess i-dropouts in the HUDF with $z$-band magnitudes less than $\sim 25$ is...
predicted to be $\sim 10$. The lack of such bright i-dropouts in the HUDF (Bouwens et al. 2006, 2007) implies that JD2 cannot be at such high redshift with 99.7 per cent confidence. Thus, future detections of massive galaxies at high redshift could be verified by looking for bright, massive neighbours.

Additional research into exactly how LBGs form in dark matter haloes and how biased they are compared to these haloes would firm up the predictions for the probability distribution of neighbours. Such work would undoubtedly include various feedback processes and environmental effects on LBG formation. Previous study indicates that LBGs are more clustered than dark matter haloes (Scannapieco & Thacker 2003), and our results for the number of neighbours are, thus, lower limits on the true values.

ACKNOWLEDGMENTS

We thank Giovanni Fazio, Kamson Lai, Evan Scannapieco, Dan Stark and Matt McQuinn for useful discussions. JAM acknowledges support from a National Science Foundation Graduate Research Fellowship.

REFERENCES

Barkana R., Loeb A., 2004, ApJ, 609, 474
Barkana R., Loeb A., 2006, MNRAS, 371, 395
Bouwens R., Illingworth G., Blakeslee J., Franx M., 2006, ApJ, 653, 53
Bouwens R., Illingworth G., Franx M., Ford H., 2007, ApJ, 670, 928
Chary R., Teplitz H. I., Dickinson M., Koo D., Le Floc'h E., Marcillac D., Papovich C., Stern D., 2007, ApJ, 665, 257
Dunlop J. S., Cirasuolo M., McLure R. J., 2007, MNRAS, 376, 1054
McLure R. J. et al., 2006, MNRAS, 372, 357
Mo H. J., White S. D. M., 1996, MNRAS, 282, 347
Mobasher B., Dickinson M., Ferguson H. C., 2005, ApJ, 635, 832
Rodighiero G., Cimatti A., Franceschini A., Brusa M., Fritz J., Bolzonella M., 2007, A&A, 470, 21
Scannapieco E., Thacker R. J., 2003, ApJ, 590, L69
Spergel D. N., Bean R., Doré O., 2007, ApJS, 170, 377
Stark D., Loeb A., Ellis R., 2007, ApJ, 668, 627
Wiklind T., Dickinson M., Ferguson H. C., Giavalisco M., Mobasher B., Grogin N. A., Panagia N., 2007, preprint (astro-ph/0710.0406v1)
Zentner A. R., 2007, Int. J. Mod. Phys. D, 16, 763

This paper has been typeset from a TeX/LaTeX file prepared by the author.