The Clustering of Lyman-break Galaxies

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\textbf{ABSTRACT}

We calculate the statistical clustering of Lyman-break galaxies predicted in a selection of currently-fashionable structure formation scenarios. These models are all based on the cold dark matter model, but vary in the amount of dark matter, the initial perturbation spectrum, the background cosmology and in the presence or absence of a cosmological constant term. If Lyman-break galaxies form as a result of hierarchical merging, the amplitude of clustering depends quite sensitively on the minimum halo mass that can host such a galaxy. Interpretation of the recent observations by Giavalisco et al. (1998) would therefore be considerably clarified by a direct determination of the relevant halo properties. For a typical halo mass around $10^{11} h^{-1} M_{\odot}$ the observations do not discriminate strongly between cosmological models, but if the appropriate mass is larger, say $10^{12} h^{-1} M_{\odot}$ (which seems likely on theoretical grounds), then the data strongly favour models with a low matter-density.

\textbf{Key words:} cosmology: theory – cosmology: observations – large-scale structure of Universe – galaxies: formation – galaxies: evolution – galaxies: haloes

1 INTRODUCTION

Developments in observational techniques have recently led to an explosion of interest in the properties of cosmological objects at such high redshifts that the lookback time at which they are seen is a considerable fraction of the age of the Universe. Such objects therefore furnish the opportunity to probe directly the evolution of galaxy clustering, bridging the gap between local observations of large-scale structure (i.e. observations with lookback times that are small compared to the age of the Universe) and observations of the cosmic microwave background radiation (where the lookback time is virtually equal to the age of the Universe).

In Matarrese et al. (1997; hereafter Paper I) and Moscardini et al. (1998; hereafter Paper II), we discussed high-redshift clustering phenomena from a theoretical perspective in order to provide a general framework within which these high-redshift phenomena can be interpreted. The formalism we derived can be used to make detailed predictions of statistical measures of clustering in specific cosmological scenarios and also makes explicit the main sources of theoretical uncertainty in these predictions. This allows one to make a realistic assessment of how models of structure formation fare in the face of results from particular observational programmes. In Paper II we applied this approach to a confrontation of different cosmological models with various galaxy clustering data, including a brief discussion of the Lyman-break galaxies (LBGs) presented in Steidel et al. (1998).

The properties of LBGs are presently undergoing a great deal of scrutiny because of the opportunities they present to study systematically the spatial clustering of galaxies at extremely high redshifts. It is the purpose of this paper to deploy the techniques of Papers I & II in a systematic comparison of a selection of currently popular structure formation models with recent results on the angular correlations of LBGs presented by Giavalisco et al. (1998).

LBGs are identified by using an efficient photometric technique that allows the identification of candidate high-redshift objects through the shifting of their Lyman limit cutoff into a particular colour filter (Steidel & Hamilton 1993). Recently Steidel et al. (1996, 1998) began a survey for $z \sim 3$ galaxies using this Lyman-break technique by observing five different fields altogether covering approximately 700 arcmin$^2$. They found 871 candidates with magnitude $R \leq 25.5$. The subsequent spectroscopic identification for 376 galaxies showed that approximately 90 per cent of the objects have $2.6 \leq z \leq 3.4$, with a median redshift $z = 3.04$ and a small r.m.s. ($\sigma_z = 0.27$).

The interpretation of LBGs is not entirely straight-
forward. They are certainly small, but are highly luminous objects. Moreover, interpreting their strong interstellar absorption lines as essentially due to gravitational motions, their masses seem to be similar to those of local bright galaxies (Giavalisco, Steidel & Macchetto 1996). This favours the interpretation that they comprise a massive halo within which the formation of a galaxy is in progress (see e.g. Baugh et al. 1998). The alternative possibility that LBGs are relatively low-mass \((\sim 10^{10} M_{\odot})\) objects with an intense starburst activity has been discussed by Somerville (1997).

The problem of the LBGs, and in particular the probability that a strong concentration at \(z \sim 3\), similar to that reported by Steidel et al. (1998), arises in particular cosmological scenarios, have been discussed by various authors by using both analytical and N-body techniques (Mo & Fukugita 1996; Jing & Suto 1998; Governato et al. 1998; Bagla 1997a; Wechsler et al. 1997; Peacock et al. 1998; Paper II). The resulting picture seems to indicate that at \(z \sim 3\) LBGs are strongly biased because they lie at the highest peaks of the density field (Kaiser 1984). They are therefore expected to be strongly clustered in all currently fashionable cosmological models. If this interpretation is correct, LBGs would be the progenitors of the population of massive ellipticals (Steidel et al. 1998) or cluster galaxies we see at \(z = 0\) (Governato et al. 1998).

The plan of this Letter is as follows. In Section 2 we describe our formalism to study the clustering at high redshift. In Section 3 we present the cosmological models used in the following analysis. The predictions of the correlation functions of the LBGs are shown in Section 4. The final discussion and conclusions are presented in Section 5.

2 CLUSTERING AT HIGH REDSHIFT

In Papers I & II we showed that the observed spatial correlation function \(\xi_{\text{obs}}\) in a given redshift interval \(z\) is an appropriate weighted average of the mass autocorrelation function \(\xi\) with the mean number of objects \(N\) and effective bias factor \(b_{\text{eff}}\), defined below in equation (3), in that range:

\[
\xi_{\text{obs}}(r) = N^{-2} \int_{z} dz_1 dz_2 \times N(z_1) N(z_2) b_{\text{eff}}(z_1) b_{\text{eff}}(z_2) \xi(r, \bar{z}),
\]

where \(N \equiv \int dz \cdot N(z)\) and \(\bar{z}\) is an intermediate redshift between \(z_1\) and \(z_2\); see Papers I & II for details.

The factor of \(b_{\text{eff}}\) which appears in equation (3) is a consequence of our lack of understanding of the details of the galaxy formation process and the consequent uncertain relationship between fluctuations in matter density \(\delta_m\) and galaxy number-density \(\delta_s\). We assume that objects with given intrinsic properties (such as mass \(M\)) and at different redshifts \(z\) can have different bias parameters, which we call \(b(M, z)\). For each set of objects, however, the bias is assumed still to be linear; it is also local (e.g. Coles 1993), in the sense that the propensity of galaxies to form at a given spatial location \(x\) depends only on the matter density at that point:

\[
\delta_s(x; M, z) \simeq b(M, z) \delta_m(x, z);
\]

so that no environmental or cooperative effects in galaxy formation (e.g. Babul & White 1991; Bower et al. 1993) are permitted. If we assume such a bias between the galaxy and mass fluctuations, the effective bias factor \(b_{\text{eff}}(z)\) which appears in equation (3) can be expressed as a suitable average of the “monochromatic” bias \(b(M, z)\) (i.e. the bias factor of each single object):

\[
b_{\text{eff}}(z) \equiv N(z)^{-1} \int_{M} d \ln M' b(M', z) N(z, M') .
\]

In principle the variable \(M\) (and its range \(\mathcal{M}\)) stands for any intrinsic properties of the object in question (e.g. mass, luminosity, etc.) on which the selection of the object into an observational sample might depend. From here on, however, we shall assume that all such properties can be reduced to a dependence on the mass of the halo within which the object (galaxy) forms. This assumption is to some extent debatable (see, e.g., Kauffmann, Nusser & Steinmetz 1997; Roukema et al. 1997) but seems a reasonable starting point in the limited range of redshifts relevant to the LBG population. Moreover, Haehnelt, Natarajan & Rees (1997) have recently shown that a good fit to the LBG luminosity function can be obtained by assuming a linear relation between star formation rate and halo mass, which implies a constant ratio of mass-to-UV-light. Henceforth in this study, therefore, \(M\) can be taken to stand for the mass of the parent halo of the LBG.

In order to predict the clustering properties of objects as a function of \(z\) we need to understand how the relationship between these objects and the underlying mass distribution evolves. In most fashionable models of structure formation the growth of structures on a given mass scale is driven by the hierarchical merging of sub-units. One begins by calculating the bias parameter \(b(M, z)\) for haloes of mass \(M\) and ‘formation redshift’ \(z_f\) at redshift \(z \leq z_f\) in a given cosmological model. The result is

\[
b(M, z | z_f) = 1 + \frac{D(z_f)}{D(z)} \left( \frac{\delta_s^2}{\sigma_M^2 D(z_f)^2} - 1 \right),
\]

where \(\sigma_M^2\) is the linear mass-variance averaged over the scale \(M\) extrapolated to the present time \((z = 0)\) and \(\delta_s\) is the critical linear overdensity for spherical collapse \((\delta_c = \text{const} = 1.686\) in the Einstein-de Sitter case, while it depends slightly on \(z\) for more general cosmologies (Lilje 1992)). The above expression originally appeared (in a slightly different form) as equation (6) of Cole & Kaiser (1989). It was then later discussed by Mo & White (1996) who also compared it with the results of numerical experiments which showed good agreement with the simple theoretical form. The general non-linear relation between the halo and the mass density contrast has been recently obtained by Catelan et al. (1998), by solving the continuity equation for dark matter haloes. A complementary study by Bagla (1997b) has further explored the clustering of haloes using numerical experiments; see also Ogawa, Roukema & Yamashita (1997). As in Paper I, we can estimate the effective bias by assuming that the objects observed in a given sur-
very represent all haloes exceeding a certain cutoff mass $M_{\text{min}}$ at any particular redshift. In other words, we assume that there is a selection function $\phi(z, M) = \Theta(M - M_{\text{min}})$ at any $z$, where $\Theta(\cdot)$ is the Heaviside step function. In this way, by modelling the linear bias at redshift $z$ for haloes of mass $M$ as in equation (1) and by weighting it with the theoretical mass–function $\bar{n}(z, M)$ which we can self-consistently calculate using the Press-Schechter (1974) theory, we can obtain the behaviour of $b_{\text{eff}}(z)$ directly. If we were to assume that rapid merging continued up to the present then this model (that in Papers I & II we called the merging model) is completely defined by the initial amplitude of primordial density fluctuations, because that determines the scale of non-linearity at each epoch $z$. This would mean that the parameter $M_{\text{min}}$ is fixed by requiring the present population of galaxies to have been entirely produced by a merger-driven hierarchy. Accordingly the present-day value of $b_{\text{eff}}(z = 0)$, which can be extracted by comparing local measurements with the mass fluctuations predicted in a given model, determines $M_{\text{min}}$.

We feel, however, that the assumption that one can compare the clustering of present-day galaxies directly with that of LBGs (which are selected in an entirely different way) is rather unsafe. Moreover, it may well be the case that instantaneous merging is not a good approximation for the later stages of clustering evolution. It is more reasonable therefore to regard $M_{\text{min}}$ as a free parameter and not attempt to relate the properties of LBGs to local galaxies. In Paper I & II we called the model obtained by letting $M_{\text{min}}$ be a free parameter the transient model, because the original theoretical motivation for it was the case of high-$z$ QSOs which have no obvious counterpart among the local galaxy population. It should, however, also be a good model for LBGs. The choice of minimum halo mass for the LBG case is not obvious, so in the following we give results for two representative cases ($10^{11} \text{ and } 10^{12} \text{h}^{-1} \text{M}_\odot$). The higher of these values is favoured by the properties of absorption lines of these objects (Steidel et al. 1998; see, however, Somerville 1997).

The computation of clustering properties using equation (1) is completed by the specification of the matter covariance function and its evolution with $z$, i.e. $\xi(r, z)$. As in Papers I & II we use a method based on the original suggestion by Hamilton et al. (1991) and developed by Peacock & Dodds (1994), Jain, Mo & White (1995) and Peacock & Dodds (1996) to calculate the evolution of perturbations into the non-linear regime. This technique also takes account of different background cosmologies, possible contributions from a cosmological constant and can be applied to a variety of initial perturbation spectra.

3 A SUITE OF TRIAL COSMOLOGIES

In this paper we consider a set of cosmological models which can all be regarded as variations on the basic cold dark matter (CDM) scenario. Although the Standard CDM model (SCDM) is no longer regarded as a good fit to observations of galaxy clustering and the microwave background, there are several alternatives with many of the same basic features but with differences in detail. In a general way, the initial (linear regime) power spectrum for all these models, which provides the initial conditions for the clustering evolution calculations discussed above, can be represented by $P_{\text{lin}}(k, 0) = P_b k^2 T^2(k)$, where we use the fitting formula of the CDM transfer function $T(k)$ as given by Bardeen et al. (1986). To fix the amplitude of the power spectrum (generally parametrised in terms of $\sigma_8$, the r.m.s. fluctuation amplitude inside a sphere of $8h^{-1}$ Mpc) we either attempt to fit the present-day cluster abundance or the level of fluctuations observed by COBE (Bunn & White 1997).

We will consider the following specific models: the SCDM model, as reference model, with $n = 1$ and a normalization consistent with the COBE data ($\sigma_8 = 1.22$); a different version of the SCDM model (hereafter called SCDM$_{cL}$) with a reduced normalization ($\sigma_8 = 0.52$) producing a cluster abundance in agreement with the observational data (Eke, Cole & Frenk 1996; see also Viana & Liddle 1996); a COBE-normalized tilted model (hereafter TCDM; see e.g. Luchin & Matarrese 1985) with $n = 0.8$, $\sigma_8 = 0.72$ and high baryonic content (10 per cent; see White et al. 1996; Gheller, Pantano & Moscardini 1998); a different version of the previous model, hereafter TCDM$_{GW}$, with a reduced normalization of the scalar perturbations ($\sigma_8 = 0.51$) taking into account the possible production of gravitational waves, as predicted by some inflationary theories (e.g. Luchin, Matarrese & Mollerach 1992; Lidsey & Coles 1992); an open CDM model (hereafter OCDM), with a matter density parameter $\Omega_m = 0.4$, a Hubble parameter $h = 0.65$ and COBE–normalized ($\sigma_8 = 0.64$); a low–density CDM model (hereafter $\Lambda$CDM) always with $\Omega_m = 0.4$ but with a flat geometry provided by the cosmological constant, with $h = 0.65$ and COBE–normalized ($\sigma_8 = 1.07$).

4 PREDICTIONS AND OBSERVATIONS

We presented calculations of the spatial correlations of LBGs in Paper II. Although the recent paper by Giavalisco et al. (1998) included an updated form of the redshift distribution, we have verified that this does not alter the predictions significantly. Observational estimates of the spatial two-point function are not yet available but Giavalisco et al. (1998) have presented results for the angular correlations of LBGs. In our previous papers we showed that, in the small–angle approximation, the observed two-point angular correlation function $\omega_{\text{obs}}(\theta)$ can be expressed as:

$$\omega_{\text{obs}}(\theta) = \int_{0}^{\infty} \left[ \int_{r_{\text{eff}}(\theta)}^{\infty} \right] \frac{\text{d}^2 G(z)}{\text{d}^2 z} \frac{N^2}{\text{d}^2 \theta^2} \text{d}^2 \theta,$$

where $r_{\text{eff}}(\theta) = a_0 \sqrt{u^2 + x^2(z)u^2}$ and $x(z)$ depends on the background cosmology; see Paper II for details. Note that the redshift distribution $N(z)$ is an observed quantity for a given survey so we do not need to spec-
Figure 1. Theoretical prediction in different cosmological models for the angular correlation function of the Lyman–break galaxies. The adopted redshift distribution and the correlation data are taken from Giavalisco et al. (1998). Open and filled squares (with 1σ errorbars) refer to two different estimators of the angular correlation, PB and LS respectively (see Giavalisco et al. 1998 for a discussion). Two different minimum masses are used to compute the effective bias: $10^{11} h^{-1} M_\odot$ (top panel) and $10^{12} h^{-1} M_\odot$ (bottom panel).

Figure 2. Theoretical prediction in different cosmological models for the projected correlation function of the Lyman–break galaxies as a function of the (comoving) separation $r_p$ (in units of $h^{-1}$ Mpc). The redshift distribution is given by Giavalisco et al. (1998). Two different minimum masses are used to compute the effective bias: $10^{11} h^{-1} M_\odot$ (top panel) and $10^{12} h^{-1} M_\odot$ (bottom panel).

$$w_{\text{obs}}(r_p) = 2 \int_{r_p}^{\infty} dr \frac{r (r^2 - r_p^2)^{-1/2}}{\xi_{\text{obs}}(r)}, \quad (6)$$

where $r_p$ is the component of the pair separation perpendicular to the line of sight. Predictions for the projected correlation function are shown in Figure 2.

Notice that the order of the amplitudes of these curves for different models is different from the angular correlation function. This is because of the different weighting by redshift and the dependence on background cosmology of the formulae.

One has to be a little cautious about the interpretation of these results because of the relatively small physical scales being probed by the sky correlations observed. The formula (4) was derived using quasi-linear arguments which are not strictly valid on small length scales. In particular, one would expect that for spatial separations of order half the initial Lagrangian radius of the haloes, their correlation function should become negative due to exclusion effects (Lacey & Cole 1994; Porciani et al. 1998). This problem is not restricted to this analysis, but is endemic in studies of this kind (e.g.
Baugh et al. 1998). In practical terms it is particularly relevant in the case of an Einstein-de Sitter model and for a large halo mass (and therefore large Lagrangian radius): if $M = 10^{12} h^{-1} M_{\odot}$ then equation (4) is formally suspect on length scales subtending an angle of about 20 arcseconds at $z = 3$ if $\Omega_{0} = 1$. Recent studies (e.g. Mo & White 1996) seem to show that the extrapolation of equation (4) onto small scales is in fairly good agreement with numerical experiments that incorporate non-linear gravitational effects on small scales that are absent from the simple theoretical calculation discussed above. We are therefore fairly confident about these predictions, given the limitations of the galaxy formation models, but this issue should be explored more fully using high resolution N-body simulations.

5 DISCUSSION

The most important results of this work are shown in Figure 1. This shows clearly that the angular clustering of LBGs is a potential powerful discriminator between cosmological structure formation models. Different models predict clearly different angular correlation functions for the LBG distribution function. The most significant cause of uncertainty is the minimum halo mass for formation of an LBG. If the critical halo mass is relatively small, e.g. $10^{11} h^{-1} M_{\odot}$, then present data to not clearly discriminate between the suite of models we discuss. On the other hand, if the minimum mass is a factor of ten larger then only the ACDM and OCDM models are allowed. In such a case the data favour a Universe with low matter-density, although they do not appear to be strongly sensitive to the presence or absence of a vacuum energy density (i.e. a cosmological constant term).

It is clearly important to decide what value of the threshold mass is more appropriate for this population of objects. Theoretical arguments generally favour the higher of the two values we have suggested here (e.g. Steidel et al. 1998; Paper II). Observationally, one might hope to determine the masses of the LBGs through their velocity dispersions. But the likeliest explanation of these objects at present seems to be that they form within rather massive haloes, but do not yet correspond to fully-assembled galaxies. Velocity dispersions might therefore merely reflect the local velocities of star-forming regions, which would lead to an underestimate of the halo mass. Such data would therefore need to be interpreted within the framework of a complete model of galaxy formation and evolution (Baugh et al. 1998; Governato et al. 1998). Such models would also establish a clearer connection the LBG population and that of nearby galaxies at $z \simeq 0$.

Despite the uncertainties surrounding the nature and identity of the LBGs, it is reassuring that their clustering properties nevertheless seem to fit within the standard gravitational instability scenario. Moreover, they also seem to be in line with the emerging consensus that we live in a Universe with a matter density which is less than the critical density.

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