The clustering of halo mergers

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ABSTRACT

We analyse the spatial distribution of halo merger sites using four numerical simulations with high time resolution of structure growth in a $\Lambda$-CDM cosmology. We find no evidence for any large-scale relative bias between mergers and randomly selected haloes of the same mass at high redshift. Given a sample of galaxies that form a Poisson sampling of halo mergers, then the amplitude of the measured clustering ought to lead to a robust estimate of the median host halo mass. In the hierarchical picture of structure growth, mergers between galaxies at high redshifts are thought to create dust enshrouded starbursts leading to increased emission in the sub-mm wavebands. Hence, a measurement of the clustering strength of SCUBA galaxies, for example, can determine whether or not they are giant elliptical galaxies in the process of formation.

Key words: galaxies: haloes – formation, cosmology: theory – dark matter

1 INTRODUCTION

A great deal of observational effort has been expended in measuring the clustering of various subsets of high-redshift galaxies. Of these, the most successful have been surveys conducted for QSOs (e.g. Croom et al. 2001), Lyman-break galaxies at $z \simeq 3$ (Giavalisco et al. 1998; Porciani & Giavalisco 2002), and $z \simeq 4$ (Ouchi et al. 2001), and EROs (Daddi et al. 2000). A particularly exciting new area is the analysis of sub-mm galaxies, made possible by the SCUBA instrument on the James Clerk Maxwell Telescope (Holland et al. 1999). Some of the most recent surveys have provided tantalising evidence that luminous sub-mm galaxies are also strongly clustered (Scott et al. in prep.; Webb et al. 2002). Planned new surveys, particularly the recently commenced SHADES (SCUBA Half Degree Extragalactic Survey, http://www.roe.ac.uk/ifa/shades) project will extend this analysis by finding 200–400 luminous sub-mm sources in a half-degree field. The SHADES data will cover separations of order 0.1–10 $h^{-1}$ Mpc at redshifts 2–4, so the clustering of objects found at these redshifts will be measured around the transition from the linear to quasi-linear regimes (see Figs. 1 and 2). Following the halo model (Jing, Mo & Boerner 1998; Seljak 2000; Peacock & Smith 2000; Ma & Fry 2000), this large-scale clustering is expected to be dominated by halo-halo clustering and the number of galaxies within each halo simply weights the relative importance of haloes with a given mass. A large-scale clustering study also avoids the additional complications involved in relating the halo properties to luminosity, since the details of the generation of radiation will mainly affect the counts and background values, rather than the fluctuations (see e.g. Knox et al. 2001). The measured clustering is therefore only dependent on the distribution of host halo masses and on any intrinsic properties of the haloes caused by their evolutionary history.

The small overlap between sub-mm and X-ray selected samples (Barger et al. 2001; Almaini et al. 2002) discourages models of sub-mm galaxies being buried AGN and favours dust enshrouded starbursts. Mergers between galaxies are often invoked as the driving mechanism for the luminous emission as they are known to cause such star-bursting activity. Detailed simulations of isolated halo mergers suggest that bursts of star formation associated with mergers between either disk or bulge/halo systems with a variety of relative masses all have lifetimes which are $<10^8$ years (e.g. Mihos & Hernquist 1996). Additionally, such mergers predominantly occur at high redshift (Lacey & Cole 1993; Percival, Miller & Peacock 2000), fitting in with our present knowledge of SCUBA sources (Blain et al. 2002). One of the simplest viable models for the distribution of sub-mm sources is therefore that they comprise a Poisson sampling of the distribution of halo-halo mergers. This ties in with proposed models of Lyman-break galaxies at $z \sim 3$, in which the emission is driven by either merger-induced starbursts (Kolatt et al. 1999) or quiescent star formation (Baugh et al. 1998). A recent comparison of the clustering predicted by various models was given by Wechsler et al. (2001).

This letter focuses on halo properties and considers the importance of halo mergers for clustering strength. The clustering of dark-matter haloes in numerical simulations has been studied in detail (e.g. Colberg et al. 2000, who analysed the Hubble volume simulation at $z = 0$). There has also been previous work looking at the clustering of haloes as a function of their intrinsic properties. Knebe & Muller (1999) showed that non-virialised haloes (plausibly those with an ongoing merger) found using a friends-of-friends
(FOF) algorithm are more biased than virialised ones. Recent work by Gottl"ober et al. (2002) also seems to find that mergers can alter the bias of haloes. However, in Gottl"ober et al. (2002), and in the Lyman-break galaxy model comparison of Wechsler et al. (2001), the distribution of host halo masses was not fixed between models. It is therefore not possible to distinguish the relative importance of halo mass and intrinsic halo properties to the clustering strength. Using numerical simulations, Lemson & Kauffmann (1999) found that only the mass function varied as a function of environment, while the formation redshift, concentration, shape and spin of each halo were independent of the environment. It is plausible that recent mergers would have affected the halo properties that they considered, and so this work implies that halo mergers should cluster in the same way as haloes in general.

In a recent paper, Kauffmann & Haehnelt (2002) analysed the distribution of quasars in a model that combined a cosmological N-body simulation with a simple merger-based prescription for AGN activation. Their paper considered the relative bias of quasars and galaxies over a range of scales, redshifts and quasar and galaxy luminosities. As part of their analysis, Kauffmann & Haehnelt also presented some evidence that the large-scale clustering of haloes with recent mergers followed that of the mean halo population of the same mass on large scales.

Given the potential importance of halo mergers for both quasar activation as discussed by Kauffmann & Haehnelt (2002) and merger-induced starbursts as discussed above, this letter extends previous work by using four numerical simulations with high time resolution of regions within a Λ-CDM cosmology to provide a detailed analysis of the large-scale clustering of mergers. The layout is as follows. In Section 2 we describe the parameters of the simulations used and the method adopted to calculate the bias of each subset of haloes, while in Section 3 we briefly introduce analytic halo bias models. Results are presented in Section 4, and we end with a discussion of these results in Section 5.

2 THE SIMULATIONS

We have completed four N-body simulations with different mass resolution using GADGET, a parallel tree code (Springel, Yoshida & White 2001). Each simulation contained 256³ particles initially distributed using the COSMICS package (http://arcturus.mit.edu/cosmics/), altered to use the transfer function fitting formulae of Eisenstein & Hu (1999). Cosmological parameters were fixed at Ω_m = 0.3, Ω_b/Ω_m = 0.15, Ω_Λ = 0.7, h = 0.7, n_s = 1. Other simulation parameters are given in Table 1. Note that although the power spectrum allowed for the signature of baryons, the particles in the simulations were all collisionless. These four complementary simulations cover a range in mass at σ8 = 0.75, and cover two different power spectrum normalisations at fixed particle mass.

Halo groups were found at 400 – 450 epochs in each simulation, separated by approximately equal intervals in ln a, using a standard friends-of-friends algorithm with b = 0.2. No attempt was made to add dynamical criteria, such as removing unbound particles. Because of the group finding algorithm used, it is important to realise that the haloes considered in this work are isolated and that the halo mass is a measure of the total mass of the system. For each halo we determine the centre of mass and use this in subsequent calculations of clustering properties. We used both the power spectrum and the correlation function to quantify clustering and have also considered a number of different estimators to calculate the correlation function with or without using the periodic nature of the simulations. All of these methods produced consistent results.

In the following we consider four samples of haloes: the set of all haloes, and three subsamples with special properties. The first subset consists of all new haloes, defined to be haloes with more than 50 per cent of constituent particles that had not been found in a halo of equal or greater mass at an earlier epoch. This is the set of haloes that have grown by at least a single particle between simulation output, and is designed to limit numerical effects: each halo is only considered to have reached a mass M at a single epoch. In the following, halo 1 (mass M_1 at time t_1) is considered to be a progenitor of new halo 2 (mass M_2 > M_1 at time t_2 > t_1) if at least 50 per cent of the particles in halo 1 are contained in halo 2.

To distinguish between mergers and haloes formed by slow accretion, we consider two subsamples of new haloes that have undergone a recent merger. In order to obtain sufficient mergers to measure the clustering, we consider all mergers that happened within 10⁸ years of a given epoch. The exact form of this lifetime is not significant for the results presented in this letter and we note that any observational signature resulting from a merger would be present for such a finite timescale. Subset 2 consists of all haloes that were defined as new within 10⁸ yrs and had two progenitors at the previous time step with masses between 25 per cent and 75 per cent of the final mass. Hence this consists of haloes that have undergone a recent violent merger, in that two progenitors with a 3:1 mass ratio or less, making up > 50 per cent of the total mass of the halo, merged within the last 10⁸ yrs. The last subsample (Subset 3) is similar except that we allow all new haloes with two progenitors with masses between 15 per cent and 85 per cent of the final mass (i.e. a merger with a mass ratio of 17:3 or less occurred within 10⁸ yrs). Due to the discrete nature of our knowledge of halo growth in time, this procedure may miss halo mergers where a progenitor forms and merges between outputs from the simulation. However, we do not expect any time-selection effects induced by this sampling to bias the spatial distribution of our sample. Before discussing the results for these four halo samples, we first discuss a simple model for predicting halo biasing, which we will use for comparison.

3 ANALYTIC MODELS OF HALO BIAS

In this Section we review the peak-background split model for the bias of the mean halo population, a model that we will use later to compare with the large-scale bias of halo mergers recovered from numerical simulations. In the peak-background split model (Cole & Kaiser 1989; Mo & White 1996; Sheth & Tormen 1999), the density field is divided into two components: δ which contains the small-scale fluctuations from which a given halo forms; and an underlying large-scale density field ζ. The effect of the large-scale
density field is to perturb the number density $n(M)$ of haloes leading to a Lagrangian bias $\Delta n(M)/n(M) = b_L \epsilon$. In addition, the growth of the background field $\epsilon$ leads to an increase in the clustering; for small $\epsilon$ this gives an Eulerian bias $b_E = 1 + b_L$. The result of this model is that the predicted bias for small $\epsilon$ is dependent on the derivative of the logarithm of the halo mass function with respect to the density. In the following we shall only consider the simple model of linear biasing that follows from this analysis, assuming that $\xi_{hh} = b_L^2 \xi_{mn}$ and $P_{hh}(k) = b_L^2 P_{mn}(k)$ in the linear regime, where $\xi_{hh}$ and $\xi_{mn}$ are the halo and mass correlation functions and $P_{hh}(k)$ and $P_{mn}(k)$ are the halo and mass power spectra.

Following standard convention, we define $\nu \equiv \delta_c/\sigma_M$ as the ratio of the density for collapse, calculated using the top-hat collapse model, to the expected rms fluctuations in top-hat spheres containing average mass $M$. There is strong evidence that the mass function determined from numerical simulations is a function of $\nu$ alone for large $\nu$ (e.g. Jenkins et al. 2001), which implies that the bias should also be a function of $\nu$ only. In the following we consider the bias calculated from the standard Press–Schechter mass

4 RESULTS

Fig. 1 shows the halo-halo correlation functions for two mass ranges calculated from the redshift slice at $z = 2$. These functions are compared to, and shown to be in good agreement with the analytic model of bias calculated from the Sheth & Tormen (1999) mass function as discussed in Section 3, and consistent results are shown to be recovered from the three simulations with $\sigma_8 = 0.75$ for the same mass ranges. Fig. 2 shows an example correlation function, again calculated at $z = 2$, but now only considering haloes that have undergone a recent merger – Subset 2 (described in Section 2). Here, we have considered three mass ranges corresponding to groups of 41–80 particles in each of the $\sigma_8 = 0.75$ function (Press & Schechter 1974; Mo & White 1996), and from fits to the mass function recovered from numerical simulations by Sheth & Tormen (1999), and by Jenkins et al. (2001). The fit to the mass function presented by Sheth & Tormen (1999) has been shown to be close to that recovered using non-standard versions of Press–Schechter theory that involve either replacing the spherical top-hat collapse model with an ellipsoidal collapse model (Sheth, Mo & Tormen 2001), or calculating the mass function using the spherical top-hat filter rather than the sharp $k$-space filter (Percival 2001).
Figure 3. The Eulerian bias squared as a function of $\nu \equiv \delta_c / \sigma_M$, calculated for 6 mass ranges corresponding to groups of 21–30, 31–40, 41–80, 81–160, 161–320 and 321–640 particles (solid lines) in each of the four simulations (rows of panels). Each line corresponds to the evolution of the clustering of haloes with time, and was calculated by comparing the power spectra of the set of haloes and of the mass. Power spectra were calculated from a $128^3$ Fourier transform covering each simulation cube, and the power was compared at wavelengths less than 0.03 times the Nyquist frequency. This was chosen as a compromise between obtaining sufficient signal and avoiding the onset of quasi-linear behaviour. The power spectra calculated for each set of haloes were averaged into 21 bins in $\ln a$ before comparison with the mass spectra. The data are compared to analytic models of the bias resulting from the standard Press–Schechter mass function (dotted line), the Sheth & Tormen (1999) mass function (dot-dash line) and the Jenkins etal. (2001) mass function (dashed line). Although the Jenkins et al. (2001) mass function was calculated for $\nu > 0.5$, they only had significant data at higher $\nu$, so the strong decrease of the bias predicted using their mass function at small $\nu$ is probably not important.

In Fig. 3 we plot the linear Eulerian bias squared as a function of $\nu$ for the four subsamples of haloes described in Section 2. We consider six mass ranges, corresponding to groups of 21–30, 31–40, 41–80, 81–160, 161–320 and 321–640 particles in each of the four simulations. Each solid line, of which there are six in each panel, corresponds to one of these mass ranges, and for such lines, $\nu$ can be considered a function of time only. The wavelength at which quasi-linear behaviour becomes dominant in the halo-halo simulations.
power spectrum is expected to be a function of both the epoch and halo mass selected. For example, the first haloes to form at high redshift will be in high density regions that are more likely (than a mass element selected at random) to have broken free from linear growth on a larger scale. Given no available model for the linear cut-off wavelength for each set of haloes, the bias was calculated from the ratio of halo and mass power spectra for $k < 10^{-5}$ times the Nyquist frequency of the $128^3$ Fourier transforms performed for each simulation box. For each panel, the evolution of the bias as a function of time can be seen to be well described by the peak-background split model. The slight turn up at large $\nu$ away from the models is consistent with the quasi-linear epoch entering the range of $k$-values considered – increasing this limit decreases the $\nu$ at which this effect starts.

5 DISCUSSION

Fig. 3 shows that the linear bias squared calculated from all four sets of haloes and all simulations follows the predictions of the peak-background split calculation using the Sheth & Tormen (1999) fit to the simulation mass function remarkably well. Comparing the peak-background split calculated using the Sheth & Tormen (1999) sets of haloes and all simulations follows the predictions of the Press–Schechter theory with a sharp $k$-space filter, which relates to much less massive objects.

However, these deviations are modest, and do not affect the primary conclusions of this letter.

Our motivation has been to provide a first step for models of the clustering of relatively small samples of high redshift objects. At such redshifts we find no evidence for a significant difference between the clustering of the set of all haloes of a given mass and any of the three subsets that we have chosen. A systematic deviation could of course be hidden within the noise, but would have to be at a level well below our current knowledge of the clustering properties of high redshift galaxies ($< 20$ per cent in the bias). A consistent environment for mergers, compared with the mean halo population, is in agreement with the work of Lemson & Kauffmann (1999) and with Press–Schechter theory with a sharp $k$-space filter, which predicts that the build-up of a halo around a small mass element is Markovian in nature. The environment of a halo at time $t$ and mass $M$ is determined by the behaviour of the trajectory at mass $> M$ which is independent of the behaviour $< M$ that contains details of the halo properties.

Several different classes of galaxy, detected at a variety of wavebands, could be related to merging haloes. Determining how the mergers relate to such luminous objects requires a great deal of additional modelling. Work along these line is still quite phenomenological in nature, although some progress has been made (e.g. Kauffmann & Haehnelt 2000, Silva et al. 2001; van Kampen et al. in preparation). However, it appears from our study that to a reasonable degree of approximation the amplitude of clustering will be a direct measure of the mass of the underlying haloes. So if we focus on SCUBA galaxies for example, a reliable measurement of the clustering amplitude should make it clear whether the objects involved are giant elliptical galaxies in the process of formation or related to much less massive objects.

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