THE IMPLICATIONS OF THE LARGE SCALE GALAXY POWER SPECTRUM FOR COLD DARK MATTER

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ABSTRACT. The APM Galaxy Survey maps the angular positions of more than one million galaxies to $b_J = 20$, covering a volume comparable to the forthcoming Sloan Digital Sky Survey. A numerical algorithm has been developed to estimate the power spectrum in three dimensions, using the angular clustering and a model for the redshift distribution of APM Galaxies. The power spectrum obtained is free from distortions of the pattern of clustering caused by the peculiar motions of galaxies. We discuss the uncertainties in the estimated power spectrum and describe tests of the algorithm using large numerical simulations. The APM Galaxy power spectrum shows an inflection at a wavenumber $k \sim 0.15h\text{Mpc}^{-1}$, with evidence for a peak or turnover in the range $k \sim 0.03 - 0.06h\text{Mpc}^{-1}$. These features can place strong constraints on Cold Dark Matter models for structure formation.

1 Introduction

The primordial power spectrum of density fluctuations in the universe is a key ingredient of any model for structure formation. Unfortunately, there are many effects that prevent a direct measurement of this quantity. Firstly, the shape of the mass power spectrum changes with redshift when the $rms$ fluctuations on a particular scale approach unity and couple to density perturbations on other length scales (e.g. Baugh & Efstathiou 1994a; Peacock & Dodds 1994). Secondly, structures are traced out by galaxies and the relation between these objects and the underlying density field is complex and may vary with redshift (Kauffmann et al 1998). An illustration of this is provided by the so-called Lyman break galaxies that have been used to probe structure in the universe at high redshift, $z \sim 3$ (see the contribution of C. Steidel to these proceedings). The clustering amplitude of Lyman break galaxies is similar to that of bright present day galaxies (Adelberger et al 1998; Giavalisco et al 1998). However, in any viable hierarchical model for structure formation, the clustering amplitude of the dark matter at this epoch is much lower than this. The Lyman-break galaxies are therefore biased tracers of the mass distribution. Finally, when the redshift of a galaxy is used to infer its spatial position, the pattern of clustering is distorted due to the peculiar motion of the galaxy resulting from inhomogeneities in its local gravitational field.

In view of these problems, there would appear to be little hope of learning anything about the distribution of dark matter in the universe by measuring galaxy clustering. However, on large scales, $\lambda > 20h^{-1}\text{Mpc}$, the above phenomena are responsible for introducing differences between the power spectra of galaxies and of mass that are either small in magnitude or which can for the most part be accurately modelled.

The forthcoming Anglo Australian 2dF and the Sloan Digital Sky Surveys will contain an order of magnitude more galaxy redshifts than the largest currently available surveys (see the contribution of A. Szalay to these proceedings). One result that will emerge from these surveys will be an accurate measurement of the power spectrum of galaxy clustering on large scales. In this article, we discuss how the parent catalogue for the 2dF Survey, the APM Galaxy Survey (Maddox et al 1996), can provide a measurement of the power spectrum on comparably large scales.

The APM Survey contains more than one million galaxies down to a magnitude limit of $b_J = 20$ and covers 4300 square degrees. The volume
Table 1. The variants of the Cold Dark Matter model used in the comparison with the APM Survey power spectrum in Figures 1 and 2. The parameter $\Gamma$ describes the shape of the power spectrum. Apart from the COBE-CDM model, the models are normalised to match the local abundance of rich clusters (Eke et al 1996).

| Model     | $\Omega_0$ | $\Lambda_0$ | $\Gamma$ | $\sigma_8$ |
|-----------|------------|-------------|----------|------------|
| cluster-CDM | 1.0        | 0.0         | 0.50     | 0.52       |
| COBE-CDM  | 1.0        | 0.0         | 0.50     | 1.24       |
| $\tau$CDM | 1.0        | 0.0         | 0.20     | 0.52       |
| $\Lambda$CDM | 0.3     | 0.7         | 0.20     | 0.93       |
| OCDM      | 0.4        | 0.0         | 0.25     | 0.76       |

covered by the angular APM catalogue is comparable to the volume that the Sloan Survey will probe. Baugh & Efstathiou (1993 – BE93; 1994b) developed a numerical algorithm to iteratively deproject the angular clustering of galaxies to measure the three dimensional galaxy power spectrum. The power spectrum is estimated in a series of wavenumber bins; hence the recovered spectrum does not rely on the assumption of a particular parametric form. Furthermore, the power spectrum obtained is free from the distortion of the pattern of clustering caused by the peculiar motions of galaxies, which affects the power spectrum measured from redshift surveys. In this article we review some of the uncertainties involved in the deprojection process and discuss the implications of the shape of the APM power spectrum for the Cold Dark Matter family of structure formation models.

2 Uncertainties in the Deprojection Algorithm

The power spectrum in three dimensions is estimated by numerically inverting Limber’s equation, which equates the angular correlation function to an integral over the spatial two point correlation function or power spectrum, and the redshift distribution of galaxies. Below we summarize some of the areas that introduce uncertainties into the estimate of the power spectrum. Full details of the deprojection algorithm and tests of accuracy and convergence can be found in BE93. The algorithm is tested against synthetic APM Survey maps made from numerical simulations by Gaztañaga & Baugh (1998).

2.1 Cosmology

The angular separation versus coordinate distance relation depends upon the choice of background cosmology. BE93 investigated the effects of different assumptions for the value of the density parameter $\Omega$ on the estimated power spectrum. There is no change in the shape of the power spectrum for different values of $\Omega$, but a small change in amplitude, of around 15%.

2.2 Galaxy Redshift Distribution

BE93 gave a simple parametric form for the redshift distribution of APM Survey galaxies. This was subsequently found to be in good agreement with the redshift distribution of galaxies in the 2dF Survey (see S. Maddox in this volume). Again, uncertainties in the median redshift of APM galaxies do not alter the shape of the recovered power spectrum, though can affect the amplitude by approximately 5%.

2.3 Approximations involved in Limber’s equation

The derivation of Limber’s equation assumes that the depth of the survey is much greater than the scale of any clustering in the survey. The largest scales on which the APM power spectrum is recovered are a significant fraction of the depth...
Figure 1. A comparison of the CDM models listed in Table 1 with the APM power spectrum on large scales. The APM power spectrum is shown by the circles and the error bars show the 1σ error on the mean obtained by splitting the APM Survey into 4 zones (taken from Table 2 of Gaztañaga & Baugh 1998). The estimates of the power used in the comparison are indicated by the filled circles. The panels show a label indicating the CDM model and the value of the bias parameter that give the best match the galaxy power spectrum over the indicated range of wavenumbers. The values of $\chi^2$ are per degree of freedom.

Gaztañaga & Baugh (1998) present tests of the deprojection algorithm using mock APM catalogues constructed by the projection of large N-body simulations. An accurate recovery of the turnover in the three dimensional power spectrum is possible in simulation boxes of side $600h^{-1}\text{Mpc}$, which is smaller than the radial extent of the APM Survey.
2.4 Evolution of galaxy clustering

The evolution of galaxy clustering is a complex interplay between the growth of fluctuations in the dark matter and galaxy formation. Fluctuations on a particular scale grow at a rate different to that predicted by linear perturbation theory when the rms variance approaches unity. At higher redshifts, the galaxy population sampled in the APM Survey becomes brighter and it is possible that these galaxies have different intrinsic clustering properties to those seen at lower redshift, though there is little evidence for this being a strong effect in this Survey (Mad- dox et al 1996; see also Tadros & Ef- stathiou 1996 and Hoyle et al 1998). The question of the evolution of the bias of APM galaxies can now be addressed using semianalytic models for galaxy formation (e.g. Benson et al 1998). In view of the low median redshift, $z \sim 0.13$ of APM galaxies to $b_J \sim 20$, both of these effects are expected to be small. For this rea-
son, BE93 used the simplest approximation that $P(k, z) = P(k)/(1 + z)^\alpha$ and adopted the case where the power spectrum is fixed in comoving coordinates, $\alpha = 0$. Maddox, Efstathiou & Sutherland (1996) adopt a value of $\alpha = 1.3$, which corresponds to clustering fixed in proper coordinates. Changing the value of $\alpha$ has essentially no effect on the shape of the power spectrum, and has only a small effect on the amplitude that is recovered, with the range of interesting values of $\alpha$ translating into a 20% uncertainty in the amplitude.

3 The Implications for Cold Dark Matter

We compare the shape and amplitude of the APM power spectrum with popular variants of the Cold Dark Matter (CDM) model in Figures 1 and 2. The model parameters are listed in Table 1. The nonlinear form of the CDM power spectrum, calculated using the formula given by Peacock & Dodds (1996) is shown by the dashed lines in the figures. One further degree of freedom, a scale independent bias is allowed. The APM power spectrum shows evidence for a turnover or flattening in slope on scales around $k \sim 0.03 - 0.06h\text{Mpc}^{-1}$ and an inflection at $k \sim 0.15h\text{Mpc}^{-1}$. We consider the best fit for the models to the turnover in the power spectrum in Figure 1 and to the inflection in Figure 2. In each panel, the best fitting value of the bias parameter is given, along with the corresponding value of $\chi^2$ per degree of freedom.

The CDM models with a shape parameter denoted by $\Gamma$ of $\Gamma = 0.5$ do the best out of the examples considered at matching the position of the turnover. These models are however the worst at matching the inflection point, which models with a lower value of $\Gamma$ reproduce better. Thus none of the CDM models considered does particularly well at matching the location of the turnover and the shape of the power spectrum at the inflection point simultaneously (see also the analysis of Gawiser & Silk 1998).

The situation could be improved if the assumption that bias is independent of scale is dropped. The form of the effective bias is then given by $b_{eff} = (P_{gal}(k)/P_{mass}(k))^{1/2}$. The effective bias required is a non-monotonic function of scale in all cases. For a CDM universe with a cosmological constant, the bias varies between $b = 0.74 \pm 0.13$ at $k = 0.03h\text{Mpc}^{-1}$ to $b = 1.00 \pm 0.11$ at $k = 0.1h\text{Mpc}^{-1}$, before becoming an antibias again of $b = 0.75 \pm 0.02$ at $k = 0.3h\text{Mpc}^{-1}$. Whilst a constant bias is undoubtably a poor approximation on scales of a few megaparsecs and smaller (Benson et al 1998), the above degree of nonmonotonic change in the bias parameter on scales of tens to hundreds of megaparsecs would appear difficult to motivate physically.

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