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Galaxy peculiar velocities and evolution-bias

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ABSTRACT
Galaxy bias can be split into two components: a formation-bias based on the locations of galaxy creation, and an evolution-bias that details their subsequent evolution. In this letter we consider evolution-bias in the peaks model. In this model, galaxy formation takes place at local maxima in the density field, and we analyse the subsequent peculiar motion of these galaxies in a linear model of structure formation. The peak restriction yields differences in the velocity distribution and correlation between the galaxy and the dark matter fields, which causes the evolution-bias component of the total bias to evolve in a scale-dependent way. This mechanism naturally gives rise to a change in shape between galaxy and matter correlation functions that depends on the mean age of the galaxy population. This model predicts that older galaxies would be more strongly biased on large scales compared to younger galaxies. Our arguments are supported by a Monte-Carlo simulation of galaxy pairs propagated using the Zel'dovich-approximation for describing linear peculiar galaxy motion.

Key words: cosmology: large-scale structure, galaxies: general, methods: analytical

1 INTRODUCTION

A number of interesting observational results have recently been published related to the bias of galaxies. On large scales $k < 0.2\,h\,\mathrm{Mpc}^{-1}$, the clustering of the 2dFGRS (Colless et al. 2003) and SDSS (York et al. 2000) main galaxies is significantly different (Cole et al. 2005; Percival et al. 2007; Sanchez & Cole 2007): There is an excess of clustering for the SDSS main sample galaxies on scales greater than $k < 0.2\,h\,\mathrm{Mpc}^{-1}$, which is not seen in the 2dFGRS galaxies. If uncorrected, this impacts on cosmological parameter measurements utilising the power spectrum shape. If the SDSS main galaxy sample is split by luminosity, we see that the bias depends on the r-band galaxy luminosity (Tegmark et al. 2004; Percival et al. 2007); and a similar trend was observed in the 2dFGRS sample (Norberg et al. 2001). If the SDSS galaxies are split in both colour and luminosity, red galaxies are more clustered than blue galaxies, but this is not a simple trend (Swanson et al. 2007). Red galaxies have the strongest relative bias on large scales independent of luminosity, while the bias of blue galaxies appears to rise monotonically with luminosity. In addition, there appear to be a number of cosmic conspiracies when considering the cosmological evolution of clustering of different galaxy classes. The amplitude of the clustering of the SDSS LRGs remains roughly constant with redshift (Eisenstein et al. 2005; Tegmark et al. 2006). In this case, the growth over time of the matter power spectrum is approximately canceled by a drop in the average bias. Croom et al. (2005) considered the evolution of the clustering amplitude of quasars in the 2dFQRS: They found that the amplitude of quasar clustering increases with increasing redshift. If quasars Poisson sample the matter distribution in the Universe, however, then we would rather expect their large-scale clustering amplitude to be proportional to the linear growth factor, decreasing with increasing redshift. There is therefore still a great deal still to understand about galaxy bias.

Models of galaxy bias depend on two different processes, in addition to the clustering of the underlying matter field: formation-bias describes the effect of galaxies forming at local extrema in the density field. These galaxies then move following the large-scale matter velocity field, resulting in evolution-bias. Although the galaxies may move locally with the matter velocity field, their peculiar velocity *distribution* does not have to match that of the matter. Ultimately, evolution-bias will lead galaxies to merge together, reducing their number density and changing the clustering properties of the population as a whole. In the simplest model of structure growth, galaxies are always hosted within a halo whose mass increases with time. In such a picture, evolution-bias is matched by the increase in the average halo mass which hosts a particular galaxy, after it has formed. A stronger evolution-bias growth indicates an increased likelihood of rapid halo mass growth through a continual merging process. In order to model the bias of an observed galaxy population we also need to include the observational selection function of the sample, which will include the galaxy formation time distributions.

Of the decomposition of galaxy bias into the two components, it is expected that the formation-bias is the largest contributor for almost all galaxy populations: the peaks formalism (Bardeen et al. 1986) predicts a strong clustering amplitude for galaxy formation at high redshift, which takes the matter field a long time to match. Formation-bias evolves strongly with redshift so, for a population of similar galaxies observed at different redshifts, this will dominate the change in the bias with time. This is different from

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evolution-bias, which gives the change in the bias of the same set of galaxies.

Driven by the observational results discussed above, we now reconsider evolution-bias from a theoretical point of view. Although galaxy formation itself is a non-linear process, the velocity field of galaxies on large scales can be sufficiently well described using linear theory. Previous work on evolution-bias has assumed a local model where the distribution of galaxy velocities matches that of the density field (Fry 1996; Tegmark & Peebles 1998). This simplifies the relevant formulae, and an analytic description of evolution-bias is achievable (this method is reviewed in Sect. 2). However, if galaxies formed at the peaks of the smoothed density field, the expected *distributions* of the galaxy peculiar velocities and of the matter field will not match (Bardeen et al. 1986). This effect is due to the nonzero covariance between the velocity field and the density gradient and complicates the evolution-bias scenario introduced by Fry (1996). We outline the theory of this approach in Sects. 3 and 4, describe the Monte-Carlo sampling technique we use to follow evolution-bias in Sect. 5 and summarise in Sect. 6.

Throughout, the cosmological model assumed is the standard ΛCDM cosmology with adiabatic initial perturbations. Choices for the relevant parameter values are: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $H_0 = 100\,h\,\mathrm{km\,s^{-1}Mpc^{-1}}$ with $h = 0.72$, $\Omega_b = 0.04$, $n_s = 1$ and $\sigma_8 = 0.8$. For the matter power spectrum we make the ansatz $P(k) \propto k^{n_s}T^2(k)$ with the transfer $T(k)$ function given by Bardeen et al. (1986) and the shape parameter given by (Sugiyama 1995). Where necessary, we impose a Gaussian smoothing on the density field with the filter scale r_{scale}, which is related to the mass scale $M_{\mathrm{scale}} = 4\pi/3\Omega_m\rho_{\mathrm{crit}}r^3_{\mathrm{scale}}$ of the objects considered.

2 ANALYTIC MODELS OF EVOLUTION-BIAS

2.1 Limit of small overdensities

Following the derivation of Fry (1996), we assume that the peculiar velocities of galaxies match those of the matter field at the same locations, $\boldsymbol{\upsilon}$. The continuity equation for the galaxy density can be written $\partial_t\rho_{\mathrm{gal}} = -\mathrm{div}(\rho_{\mathrm{gal}}\boldsymbol{\upsilon})$, and for the matter $\partial_t\rho_{\mathrm{CDM}} = -\mathrm{div}(\rho_{\mathrm{CDM}}\boldsymbol{\upsilon})$. By defining $\delta \equiv \rho/\bar{\rho} - 1$, the continuity equation for the matter reduces to $\partial_t\delta_{\mathrm{CDM}}(a) = -\mathrm{div}\boldsymbol{\upsilon}(a)$, for small δ_{CDM}. Solving the system consisting of the continuity and Euler-equations yields the result that the evolution of δ_{CDM} is driven by the standard linear growth factor $D(a)$, so that $\delta_{\mathrm{CDM}}(a) = D(a)\delta_{\mathrm{CDM}}(1)$, with $D(1) = 1$ at present day.

If $(\delta_{\mathrm{gal}} - \delta_{\mathrm{CDM}})$ is small everywhere, then $\delta_{\mathrm{gal}}(a)$ satisfies the same linear continuity equation as $\delta_{\mathrm{CDM}}(a)$, giving $\dot{\delta}_{\mathrm{gal}}(a) = -\mathrm{div}\boldsymbol{\upsilon}(a)$. In this limit,

$$\delta_{\mathrm{gal}}(a) = \delta_{\mathrm{gal}}(1) + (D(a) - 1)\delta_{\mathrm{CDM}}(1). \tag{1}$$

Note that the assumption of small $(\delta_{\mathrm{gal}}-\delta_{\mathrm{CDM}})$ is important, because the densities of the dark matter and galaxy fields need to be matched in the full continuity equations, in order for the expected growth in δ_{gal} to be equal to that of δ_{CDM}. This assumption is equivalent to stating that the distribution of the peculiar velocities of the galaxies is the same as that of the matter field.

2.2 Starting from linear bias

This idea has been extended by Fry (1996), who considered a galaxy overdensity field with a linear bias at present day $\delta_{\mathrm{gal}}(1) = b(1)\delta_{\mathrm{CDM}}(1)$. Substituting this into eqn. (1) gives $\delta_{\mathrm{gal}}(a) = [D(a) - 1 + b(1)]\delta_{\mathrm{CDM}}(1)$. In this model the linear bias is is related to the growth function by

$$b(a) = \frac{D(a) - 1 + b(1)}{D(a)}. \tag{2}$$

Furthermore Tegmark & Peebles (1998) considered the evolution-bias of galaxies following the more general stochastic bias model of Dekel & Lahav (1999) and derive cross correlations between the matter density and galaxy fields. To simplify the analysis we follow Tegmark & Peebles (1998) and define the vector

$$\boldsymbol{x}(a) = \begin{pmatrix} \delta_{\mathrm{CDM}}(a) \\ \delta_{\mathrm{gal}}(a) \end{pmatrix}. \tag{3}$$

Forcing the galaxy overdensity field to obey the bias model of Dekel & Lahav (1999) at present day allows the galaxy and dark matter distributions to be related by an additional correlation coefficient r. At present day, the covariance matrix can be written

$$\mathbf{C}(1) \equiv \langle \boldsymbol{x}(1)\boldsymbol{x}^t(1)\rangle = \langle\delta^2_{\mathrm{CDM}}(1)\rangle \begin{pmatrix} 1 & b(1)r(1) \\ b(1)r(1) & b(1)^2 \end{pmatrix}. \tag{4}$$

In this notation, the continuity equation for the galaxy overdensity field coupled with the linear growth factor for the matter gives

$$\boldsymbol{x}(a) = \mathbf{M}(a)\boldsymbol{x}(1)\ , \text{ where } \mathbf{M} \equiv \begin{pmatrix} D(a) & 0 \\ D(a) - 1 & 1 \end{pmatrix}. \tag{5}$$

The corresponding evolution of the covariance matrix $\mathbf{C}(a) = \mathbf{M}(a)\mathbf{C}(1)\mathbf{M}^t(a)$ shows that the evolution of the galaxy overdensity field can be rewritten in terms of $r(a)$ and $b(a)$ (Tegmark & Peebles 1998), and that the bias model does not change its form. For $r = 1$, the formula reduces to the relation of Fry (1996).

2.3 Bias for Gaussian random fields

In work predating Fry (1996) and Tegmark & Peebles (1998), Bardeen et al. (1986) considered the evolution of bias for galaxies that form at peaks of the density field after smoothing on a certain mass scale. On large scales, the peak density field can be considered as a continuous Gaussian random field itself, statistically independent and uncorrelated with the background, which drives the dynamics of the galaxies. The galaxy and matter density field evolve independently due to the peak-background split, as independent k-modes are important for their respective evolution.

Using this model Bardeen et al. (1986) showed that the large-scale bias evolves as $b(a) \propto \delta_c/\sigma_M(a) + 1$ for a smoothed Gaussian density field with variance $\sigma_M(a)$, where δ_c is the overdensity threshold above which galaxies form. On linear scales, the variance of the density field $\sigma_M(a)$ is proportional to the linear growth factor $\sigma_M(a) \propto D(a)$. Consequently, if we normalise the bias at present day, we recover eqn. (2) for the evolution of the bias. A key assumption made in the derivation is the treatment of the galaxy distribution as a continuous field and that the evolution in the comoving number density of peaks is driven by the evolution of the background density, which is in effect a reformulation of the continuity equation for the galaxy field: Forcing the number density of galaxies to evolve with the background density is akin to the assumption of small $(\delta_{\mathrm{gal}} - \delta_{\mathrm{CDM}})$ that led to the linearised continuity equation for the galaxy field.

3 STRUCTURE GROWTH FROM PAIR VELOCITIES

The above descriptions of evolution-bias can also be understood in terms of the peculiar velocities of a discrete set of galaxies. The variance of the peculiar velocity distribution for each galaxy is

$$\sigma_v^2 = \frac{[aH(z)f]^2}{2\pi^2}\int_0^\infty dk\,P(k), \tag{6}$$

where $H(z)$ is the Hubble parameter and $f \equiv d\log D/d\log a$. If we assume that δ is small everywhere, the expected infall velocity is zero for all pairs of galaxies: we are as likely to choose galaxies that are moving apart (in comoving space), as peaks moving together. If galaxy peculiar velocities were uncorrelated, the galaxy density field would not develop clustering as any initial clustering pattern will be destroyed by the random diffusion. This is not the case for velocity fields driven by correlated Gaussian random overdensity fields as the velocities of galaxy pairs of separation r are correlated according to

$$C_v(r) = \langle \boldsymbol{v}_1 \cdot \boldsymbol{v}_2\rangle = \frac{[aH(z)f]^2}{2\pi^2}\int_0^\infty dk\,P(k)j_0(kr). \tag{7}$$

Velocities of pairs of galaxies will be strongly correlated when r is small as both galaxies preferentially move in the same direction, being part of the same bulk flow, but velocities of galaxy pairs with large separations are less strongly correlated. This difference means that there is a net influx of galaxy pairs from large to small separations, which leads to the growth in the clustering strength. For a pair of galaxies of separation r, the variance of the peculiar velocity difference is

$$\langle|\boldsymbol{v}_1 - \boldsymbol{v}_2|^2\rangle = 2[\sigma_v^2 - C_v(r)], \tag{8}$$

where σ_v^2 is a diffusion term.

Changing the selection criteria of galaxy pair-velocities naturally changes the evolution of galaxy clustering. An extreme example of a galaxy field with an evolution-bias would be the assumption that galaxies only form at locations where the peculiar velocity $\boldsymbol{v} = 0$. After formation, galaxies at these locations do not move, and the galaxy overdensity and clustering properties are constant in comoving space. In contrast to the model proposed by Bardeen et al. (1986), this is not physically motivated, because there is no a-priori reason to link places in the velocity field where $\boldsymbol{v} \simeq 0$ with galaxy formation. The derivation leading to eqn. (1) breaks down for this model because it relied on matching the galaxy and matter overdensity fields, which is clearly broken. In this situation, the galaxies still locally "move with the matter" although the *distribution* of galaxy velocities does not match the *distribution* of velocities of the dark matter.

4 EVOLUTION-BIAS IN THE PEAKS FORMALISM

We now consider the evolution of a set of galaxies that form at the peaks of a smoothed density field, where there is the most rapid increase in density. After formation, the galaxies leave the peaks, whose positions are fixed in comoving space, and move with the matter flow.

We wish to estimate the average velocity of a matter concentration at a peak in the field, so we will need to consider the density and velocity fields after smoothing by a filter of width $r_{\rm smooth}$. The velocity dispersion and correlation can be calculated by replacing $P(k)$ with the smoothed power spectrum $\bar{P}(k)$ in eqns. (6), (7) and (8). For large separations $r \gg r_{\rm smooth}$, the Bessel function in eqn (7) takes precedence over the smoothing of the field, and $C_v(r)$ tends towards the value for the unsmoothed field. In contrast, the variance of the velocity for each galaxy σ_v^2 (eqn. 6), which is independent of r, does depend on the smoothing applied to the field. The effects of the smoothing scale on σ_v^2 and $C_v(r)$ are shown in Fig. (1), for a pair separation of $200\,h^{-1}$ Mpc.

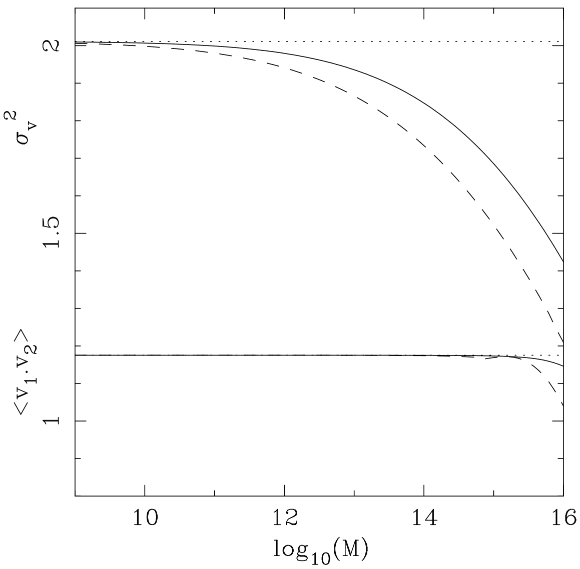

Figure 1. The expected variance for velocities in a Gaussian random field smoothed with a Gaussian filter (solid lines), and for the unsmoothed field (dotted lines), plotted against smoothing scale parametrised by the mass enclosed within the filter (upper lines). The expected velocity correlation between two points separated by $200\,h^{-1}$ Mpc, under the same assumptions are shown by the lower lines. The decrease in velocity variance caused by additionally selecting sampling points with vanishing gradient in the smoothed density field is indicated by the dashed lines.

In order to select peaks in the smoothed density field, we need to set two further constraints on the galaxy locations: The density gradient has to be zero, and the local curvature needs to be positive definite. Because the velocities are correlated with the density gradient, placing galaxies at locations where the gradient is zero reduces the velocity variance σ_v^2 from that of eqn (6) by a factor $(1-\gamma_v^2)$ (Bardeen et al. 1986; Szalay & Jensen 1987; Peacock et al. 1987), where

$$\gamma_v = \frac{\sigma_0^2}{\sigma_{-1}\sigma_1}, \quad \text{and} \quad \sigma_j^2 = 4\pi\int_0^\infty dk\,k^{2j+2}P(k). \tag{9}$$

For a smoothed field, $P(k)$ needs to be replaced by $\bar{P}(k)$ with the consequence that $\gamma_v \to 1$ as $r_{\rm smooth} \to \infty$. In the limit of large r, the velocity correlation function is unchanged by the peak constraint: In this limit, velocity-velocity correlations dominate over velocity-gradient, or gradient-gradient correlations because of the additional k^{-1} terms in the velocity-dependent integrands. The effect of including both the smoothing of the field and the zero-gradient selection criteria on σ_v^2 and $C_v(r)$ is shown in Fig. (1), for a pair separation of $200\,h^{-1}$ Mpc.

The reduction of the dispersion element of eqn. (8), while keeping the growth component fixed will lead to a scale-dependent increase in the 2-point galaxy correlation function (Regos & Szalay (1995) also comment on this). From this it is clear that propagating galaxies along their velocity vectors does not preserve the shape of the correlation function, and the bias evolution formalism developed in Sect. 2 breaks down.

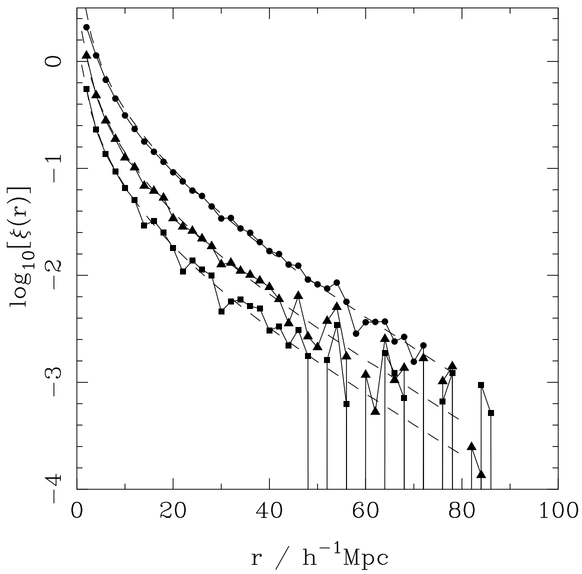

Figure 2. The correlation function at $z = 0$ (circles), $z = 1$ (triangles) and $z = 2$ (squares) calculated from a Monte-Carlo realisation of 10^8 independent pairs of points in a Gaussian random field. These are compared with the expected correlations for linear growth (dashed lines). On large scales, $\xi(r)$ becomes negative because we only sample pairs of galaxies with initial separation $< 100\,h^{-1}$ Mpc.

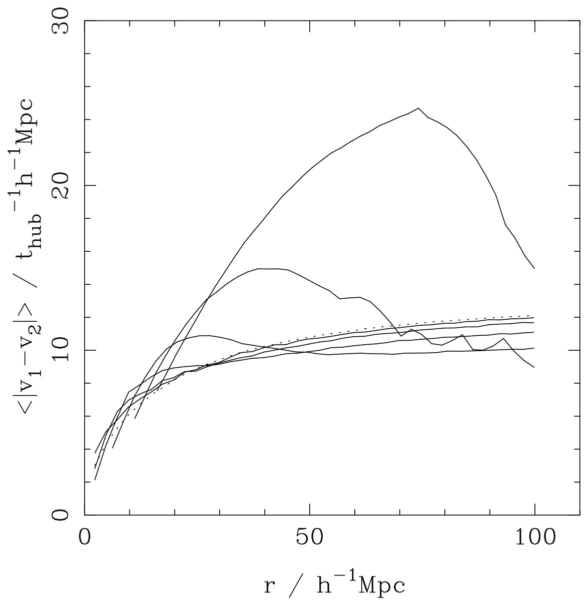

Figure 3. The expected amplitude of the pair-velocity as a function of pair-separation for peaks selected for halos of mass $10^{10...15}\,M_\odot$ (solid lines). Increasing the halo mass leads to larger infall velocities. These curves were calculated from 10^7 independent pairs of peaks, although each was weighted as described in the text, so these correspond to a much smaller effective number of pairs. The expected pair-velocity for locations selected at random in the matter distribution is shown by the dotted line.

5 MONTE-CARLO SIMULATION OF GALAXY PAIR PROPERTIES

We use the formalism introduced by Regos & Szalay (1995) to set up a Gaussian random process for determining velocity variances and correlations in the large-scale structure. Regos & Szalay (1995) show how a 26×26 covariance matrix can be constructed for the multi-variate Gaussian distribution of the properties (overdensity, 3 gradient components, 6 curvature components and 3 velocity components) of pairs of points in a smoothed Gaussian random field. The matrix depends on the power spectrum moments given in eqn. (9) and from the functions of the pair separation r given by

$$K_{\ell m} = 4\pi \int_0^\infty dk\, k^m\, j_l(kr)\bar{P}(k). \tag{10}$$

Using these covariance matrices, we can randomly draw realisations of the properties of pairs of points in the field, assuming they follow a multi-variate Gaussian distribution. We can also add constraints on the pairs selected, such as that they must both be at a peak in the field.

We first demonstrate that this procedure can reproduce the linear growth expected for the matter field. We have produced a Monte-Carlo realisation of 10^8 pairs of galaxies using the procedure described above, without any additional constraints on pair selection. This corresponds to choosing random locations in a matter field. The peculiar velocities were then used to estimate the motion of galaxies in linear structure formation using the Zel'dovich approximation. This is applicable for small displacements, and should therefore accurately describe the initial effect of evolution-bias after galaxy formation. The dynamical model is affected by the properties of the particular dark energy model through the growth function $D(a)$, which affects the peculiar velocities. From these data, we have calculated $\xi(r)$ for $z = 0, 1, 2$, assuming that the galaxy pairs evolve from an initial unclustered comoving distribution (as expected for the matter in the Universe, which is initially homogeneous). The correlation functions are plotted in Fig. 2 showing excellent agreement with the expected linear evolution.

We now consider galaxies that form at peaks in this field. The additional criteria applied within our Monte-Carlo procedure to ensure that we select peaks are

(i) overdensity threshold $\delta > \delta_c = 1.69$,
(ii) gradient $\nabla\delta = 0$,
(iii) positive definite curvature matrix.

Peaks are rare, so simply selecting peaks from pairs chosen at random is computationally unfeasible. Instead, where possible, we force the properties that are required (for example, we only sample from the tail of a Gaussian distribution to select $\delta > \delta_c$), and then weight the chosen pairs by the likelihood of making that selection in a full multi-variate analysis. This gives a weighted distribution with the same statistical properties as selecting a true Monte-Carlo sample, but is computationally faster for determining the properties of the distribution.

The expected amplitude of the pair-velocity $\langle|\boldsymbol{v}_1 - \boldsymbol{v}_2|\rangle$ for galaxies selected at peaks, is plotted in Fig. 3 for halos of mass $10^{10...15}\,M_\odot$. The expected pair-velocities differ from those of the mass, because peaks are more likely to be approaching each other than moving apart at large separations. The evolution in the correlation function depends on the derivative of the expected pair-velocity, which controls the net change of pairs with a given separation (when the distances travelled are small). As we move to increasing separation, the peak pair-velocity increases rapidly, but then turns over and starts to decrease. This will lead to the correlation function decreasing on small scales, and increasing on large scales.

We have constructed a weighted Monte-Carlo distribution of 3×10^8 galaxy pairs selected at the peaks in a Gaussian random field, smoothed by a Gaussian filter with width corresponding to a

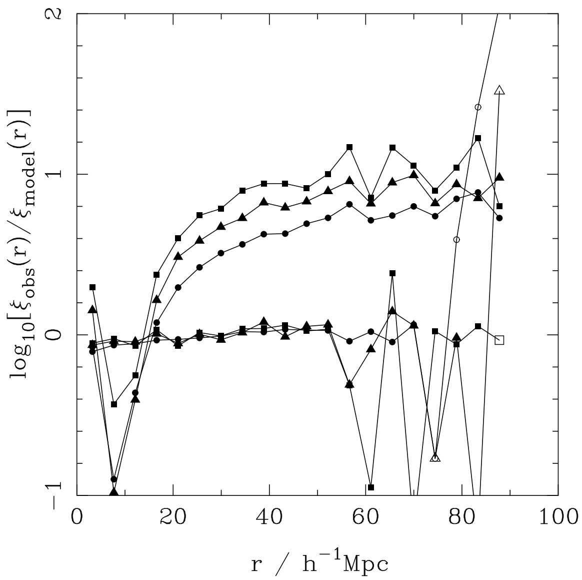

Figure 4. The correlation functions recovered from propagating pairs of galaxies along their peculiar velocities, divided by those expected from linear evolution of the density field. Correlation functions at $z = 0$ (circles), $z = 1$ (triangles) and $z = 2$ (squares), were calculated from a Monte-Carlo realisation of 10^8 independent pairs of points in a Gaussian random field (lower lines), and from 3×10^8 weighted peaks in a Gaussian random field smoothed with a Gaussian filter corresponding to a halo mass of 10^{12} $M_\odot$ (upper lines).

halo mass 10^{12} $M_\odot$. In order to demonstrate the effect of peak selection on the galaxy correlation function, we have followed the evolution of galaxies pairs from an initially unclustered distribution. This matches the analysis of pairs of galaxies selected at random from the matter distribution that led to Fig. 2, but selects special locations in the velocity field. The ratios between the recovered galaxy correlation functions and those expected for the matter at $z = 0, 1, 2$, are shown in Fig. 4. As we move from small to large scales, the bias at any redshift initially decreases, because of the change in expected infall velocity shown in Fig. 3, but then increases beyond that of the matter field, as expected from the analytic arguments discussed in Sect. 4. Due to the fact that galaxies only pick up their peculiar velocities after formation, this plot should not be interpreted as giving the actual galaxy correlation functions for peaks. To do this, we would need to specify galaxy formation times and their spatial distribution (or formation-bias). The relative effect of the evolution-bias on $\xi(r)$, however, should be the same, and this plot demonstrates that bias is not a simple function of scale. The large-scale bias is a decreasing function of time, as the amplitude of the clustering of the matter field grows to match the strong evolution-bias predicted at early times.

6 SUMMARY AND DISCUSSION

We have considered a decomposition of galaxy bias into formation-bias and evolution-bias. The formation- and evolution-biases are inter-related, with one tending to lead to the other: By choosing special locations for galaxy formation, we also tend to choose locations that lead to group evolution that is very different from that of particles selected at random in the matter field. By analysing models of evolution-bias, we have argued that this component of bias has some interesting properties within the peaks model. We have demonstrated this from both analytic arguments and a Monte-Carlo procedure based on the work of Regos & Szalay (1995). Evolution-bias provides a mechanism for producing a scale-dependent bias in 2-pt correlation measurements, whose importance grows as the galaxies move, and consequently depends on the time since galaxy formation. Note that the overall bias of a galaxy sample would, in general, be expected to be a decreasing function of time because this depends on the increasing amplitude of the clustering of the matter field.

The inclusion of evolution-bias in a combined model of galaxy bias would predict that older galaxies have a scale dependent bias with a correlation function whose shape is less like that of the matter field than a population of younger galaxies. In the most simple model, the red luminosity of an individual galaxy increases and then fades with time. Galaxies can also merge together, forming larger, brighter objects. The oldest field galaxies tend to be faintest, and should be most affected by scale-dependent biasing on large scales. Such a description might explain why the SDSS LRGs and 2dFGRS galaxies seem to match a simple prescription for galaxy bias, while the SDSS main galaxies do not (Sanchez & Cole 2007): The SDSS main galaxies sample would contain these old field galaxies. The evolution-bias considered here would also impact on measurements of the Baryon Acoustic Oscillation scale length from the power spectrum or correlation function. Further simulations, such as provided by semi-analytic techniques, which combine formation and evolution-bias, are required to consider this mechanism in more detail and apply it to specific galaxy types.

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