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The effects of alignment and ellipticity on the clustering of galaxies

Marcel P. van Daalen[1,2]*, Raul E. Angulo[1] and Simon D. M. White[1]
[1] *Max Planck Institute for Astrophysics, Karl-Schwarzschild Straße 1, 85741 Garching, Germany*
[2] *Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands*

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ABSTRACT

We investigate the effects of halo ellipticity and alignment with larger-scale structure on the galaxy correlation function. We base our analysis on the galaxy formation models of Guo et al. (2011), run on the Millennium Simulations. We quantify the importance of these properties of the galaxy distribution by randomizing the angular positions of satellite galaxies within haloes, either coherently or individually, while keeping the distance to their respective central galaxies fixed. We find that the effect of disrupting the alignment with larger-scale structure is a ~ 2 per cent decrease in the galaxy correlation function around $r \approx 1.8\,h^{-1}\,\mathrm{Mpc}$. Sphericalizing the ellipsoidal distributions of galaxies within haloes decreases the correlation function by up to 20 per cent for $r \lesssim 1\,h^{-1}\,\mathrm{Mpc}$. Similar results apply to power spectra and redshift-space correlation functions. Models such as those based on the Halo Occupation Distribution, which adopt a spherically averaged profile for the galaxy distributions within haloes, will therefore significantly underestimate the clustering on sub-Mpc scales.

Key words: cosmology: theory – cosmology: large-scale structure of Universe

1 INTRODUCTION

Investigating how matter is organized in our Universe is one of the key ways in which we can test the validity of cosmological models and constrain their parameters. By comparing theoretical predictions to observed measures of structure, such as the galaxy correlation function or the matter power spectrum, one can reject some models and fine-tune others. It is, however, important to keep in mind the limitations of theoretical models, both numerical and analytical, when making this comparison, as these may limit the applicability of the results.

There are various ways in which one can predict the organization, or “clustering”, of matter and galaxies theoretically. One can use fully hydrodynamical simulations, in which dark matter, gas and stars are treated separately, to follow directly the formation and evolution both of dark matter haloes and of the galaxies within them. For a recent review of the numerical methods behind such simulations, see Springel (2010). However, such models are computationally expensive, and are sensitive to the *ad hoc* subgrid recipes required to include critical processes like star formation and feedback.

An alternative, first implemented by Kauffmann et al. (1999) (see also Springel et al. 2001, 2005), is to combine N-body simulations of the growth of dark matter structures with semi-analytic models of galaxy formation (e.g. White & Frenk 1991, Kauffmann, White & Guiderdoni 1993, Cole et al. 1994; see Baugh 2006 for a review). A great advantage of semi-analytic simulations is that they require comparatively little CPU time even for a large underlying N-body simulation. This allows them to be run many times and on many haloes, so that one can explore the physical processes and the associated parameters that would result in galaxies whose properties agree with selected observational data (such as the galaxy stellar mass, luminosity or correlation functions). Such semi-analytic simulations do not focus on the properties of individual objects, but rather on the underlying statistical properties of the entire population. In this way, the relative importance of different physical processes can be examined as a function of the time and place where they are occurring.

Yet another alternative is to take the statistical approach one step further. If one is interested only in the present-day clustering of galaxies, the physical processes associated with their formation and evolution may not be relevant. Thus, one can populate the haloes in an N-body simulation with galaxies using a purely statistical model that depends on certain halo properties, most notably their mass. Galaxy clustering can then be described in terms of the clustering of the haloes. This approach is known as halo occupation distribution modelling, or sim-

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* E-mail: daalen@mpa-garching.mpg.de

ply HOD modelling (see Cooray & Sheth 2002 for a review). Typically, central and satellite galaxies are treated separately, as each halo will contain one and only one of the former but may contain none or many of the latter (Kauffmann et al. 1999, Kravtsov et al. 2004, Zheng et al. 2005). The satellite galaxies assigned to a halo are usually assumed to be spherically distributed following a standard profile such as that of Navarro, Frenk, & White (1997, NFW). Attempts at including substructure or an environmental dependence have also been made (e.g. Giocoli et al. 2010, Gil-Marín, Jimenez & Verde 2011). Note that by assuming spherical symmetry some information is lost. As the simulations of Davis et al. (1985) first showed, cold dark matter haloes are typically strongly ellipsoidal. If the distribution of galaxies follows the mass distribution, this would leave an imprint on the galaxy correlation function on small scales. Furthermore, halo ellipticity may also have an effect on larger scales. If the galaxy distributions in neighbouring haloes are aligned, as expected from tidal-torque theory, this will boost the correlation on scales corresponding to the typical separations between haloes.

The ellipticity and intrinsic alignment of dark matter haloes and their galaxy populations has been the subject of many earlier studies, such as those by Carter & Metcalfe (1980), Binggeli (1982), West (1989), Splinter et al. (1997), Jing & Suto (2002), Bailin & Steinmetz (2005) and very recently Paz et al. (2011) and Smargon et al. (2011). Most relevant to the current work is the study by Smith & Watts (2005), who investigated the effects of halo triaxiality and alignment on the matter power spectrum in the halo model framework. Inspired by the results of simulations, they took a purely analytical approach in which they re-developed the halo model to account for ellipsoidal halo shapes.

In this Letter, we expand upon previous work by investigating the effects of alignment and ellipticity on the galaxy correlation function using the Millennium Simulation (Springel et al. 2005) and the semi-analytic models of Guo et al. (2011). In Section 2, we discuss these simulations, as well as our methods for quantifying the effects of alignment and ellipticity. We show our results in Section 3, and present our conclusions in Section 4.

2 METHODS

2.1 Simulation and SAM

We make use of the galaxy catalogues generated by Guo et al. (2011, hereafter G11), who implemented galaxy formation models on the Millennium Simulations (Springel et al. 2005, Boylan-Kolchin et al. 2009). The Millennium Simulation (MS) is a very large cosmological N-body simulation in which 2160^3 particles were traced from redshift 127 to the present day in a periodic box of side $500\,h^{-1}\,$Mpc, comoving. The Millennium-II Simulation (MS-II) follows the same number of particles in a box of side $100\,h^{-1}\,$Mpc and so has 125 times better mass resolution. Both simulations assume a ΛCDM cosmology with parameters based on a combined analysis of the 2dFGRS (Colless et al. 2001) and the first-year WMAP data (Spergel et al. 2003). These cosmological parameters, given by $\{\Omega_{\rm m}, \Omega_{\rm b}, \Omega_\Lambda, \sigma_8, n_{\rm s}, h\} = \{0.25, 0.045, 0.75, 0.9, 1.0, 0.73\}$, are not consistent with the latest analyses of the CMB data, for example the seven-year WMAP results (Komatsu et al. 2011). In particular, the more recent data prefer a lower σ_8 value.[1] We will only make relative comparisons between clustering statistics here, and do not expect our results to be significantly influenced by these small parameter differences.

The galaxy formation models of G11 allow galaxies to grow at the potential minima of the evolving population of haloes and subhaloes in the simulations. Each Friends-of-Friends (FoF) group contains a central galaxy at the potential minimum of its main subhalo, and may contain many satellite galaxies at the centres of surrounding subhaloes. In some cases, due to tidal effects, a satellite galaxy may be stripped of its dark matter to the point where its subhalo is no longer identified as a bound substructure, turning the galaxy into an "orphan". Such galaxies follow the orbit of the dark matter particle that had the highest binding energy immediately before subhalo disruption, except that their distance to the central galaxy is artificially decreased until they merge with it in order to mimic the effects of dynamical friction. The models also include treatments of star formation, gas cooling, gas stripping, metal enrichment, supernova and AGN feedback, and galaxy mergers. For more details about the SAM, as well as the treatment of different types of galaxies, we refer to G11. For our purposes, it is enough to note that the predicted clustering of galaxies is quite a close match to that seen in the Sloan Digital Sky Survey (Guo et al. 2011).

2.2 Calculation of the galaxy correlation function

The galaxy two-point correlation function, $\xi(r)$, measures the clustering of galaxies as a function of scale. It effectively encodes the excess probability of finding a pair of galaxies at a given separation r, relative to the expectation for a uniform random distribution. In what follows, we will be interested in scales $30\,h^{-1}\,\mathrm{kpc} < r < 50\,h^{-1}\,\mathrm{Mpc}$, as these are both well-resolved and well-sampled by the simulation. In order to get accurate results over this full range, we calculate the correlation function by direct pair counts on small scales (i.e. $r \lesssim 4\,h^{-1}\,\mathrm{Mpc}$) and use an approximate but accurate method to calculate it on intermediate and large scales.

A direct calculation of this function scales as the number of galaxies squared and is thus unfeasible for the large sample analysed here. We therefore speed up the calculation by mapping galaxies onto a grid, and we correlate the mean density contrast in each grid cell with that of every other (a method previously employed by, for example, Barriga & Gaztañaga 2002, Eriksen et al. 2004 and Sánchez, Baugh & Angulo 2008). We improved the performance on intermediate scales by folding the density field onto itself before its autocorrelation is calculated (see e.g. Jenkins et al. 1998). We do not go into these methods here, but note that tests against higher-accuracy calculations show that the error in the ratio of the correlation functions, which is the relevant quantity for our main results, is less than 1 per cent on all scales considered.

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[1] See Angulo & White (2010) for a method to correct for this.

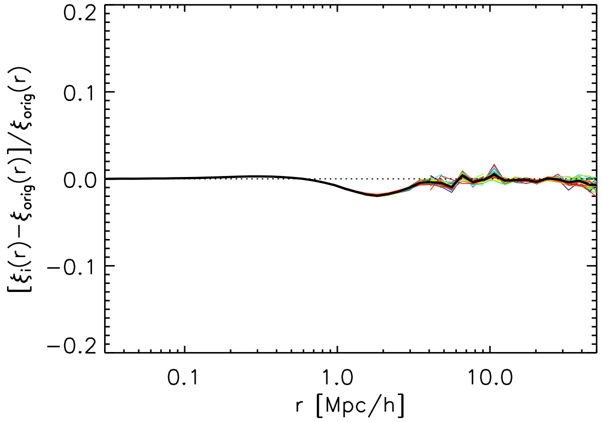

Figure 1. The effect of halo alignment on the galaxy correlation function. The x-axis shows the real-space separation r, while the y-axis shows the fractional difference between the correlation function after random bodily rotations are applied, and that of the original, unrotated sample. All simulated galaxies with $M_* > 10^9\,h^{-1}\,\mathrm{M}_\odot$ from the $z = 0$ catalogue of G11 have been used here. The bin size is roughly 0.07 dex. Each of the 25 thin, coloured lines represents a different set of random rotations, and the thick, black line shows the average of these. There is a clear signal around $r \approx 1.8\,h^{-1}\,\mathrm{Mpc}$, where the correlation function is lowered by roughly 2 per cent.

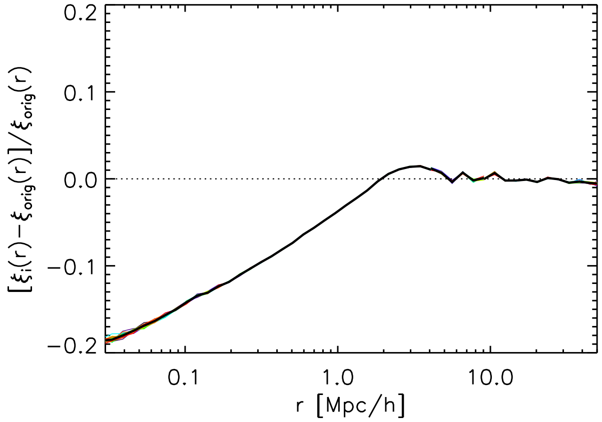

Figure 2. The effect of halo ellipticity on the galaxy correlation function. The bin size, axes and lines are as in Figure 1, although the bodily rotations have been replaced by random independent rotations of satellites around their central galaxies. A peak of $1-2$ per cent can be seen around $r \approx 3.5\,h^{-1}\,\mathrm{Mpc}$, but the largest effect is seen on small scales, where the correlation function is systematically lowered by up to ~ 20 per cent. Note also that the scatter has been greatly reduced relative to Figure 1. This is mainly due to the larger number of random rotations used when rotating satellites separately.

2.3 Testing the importance of alignment and ellipticity

During their lifetime, haloes merge and may accrete more subhaloes. The accretion of mass is not isotropic since matter flows in preferentially along filaments (see e.g. Tormen, Bouchet & White 1997, Colberg et al. 1999 or more recently Vera-Ciro et al. 2011). As a result, the distribution of subhaloes and thus galaxies within a FoF group is generally not isotropic either, but is instead approximately ellipsoidal, following the mass and aligning with surrounding large-scale structure (see e.g. Angulo et al. 2009). To test whether alignment with neighbouring structure has an effect on clustering statistics, we randomly rotate the haloes around their centres and see if this systematically alters the galaxy correlation function. More precisely, we rotate the satellite population of each FoF group bodily around the central galaxy to a new randomly chosen orientation, and we repeat this process for every FoF group in the simulation. We stress that this transformation preserves the numbers, properties, and relative positions of the galaxies in every halo; only the orientations of the distributions change. We then calculate the galaxy correlation function for the new distribution, and compare it to the original. If alignment with large-scale structure is important, one would expect to see the correlation decrease systematically on scales slightly larger than individual haloes. To estimate the uncertainty in our results, we have repeated this process 25 times, each time with a different set of randomly chosen angles.

The effect of the halo ellipticity is tested in a similar way. Here, we randomly rotate the position of each individual satellite galaxy around its central, rather than rotating all satellites together. In this way, the galaxy distribution within each halo is sphericalized. Since the distribution of galaxies within haloes is typically ellipsoidal, this process should increase the average distance between galaxies, thus decreasing the correlations between galaxies in the same halo.

3 RESULTS

We will first discuss our results for "bodily" rotations, which test the effect of halo alignment. Figure 1 shows the fractional difference between the correlation functions of the "rotated" and original samples, plotted against the real-space separation r. We have only used those galaxies from the catalogue generated by G11 that have a stellar mass $M_* > 10^9\,h^{-1}\,\mathrm{M}_\odot$, as the Millennium Simulation is not complete below this limit. This provides a sample of 5 200 801 galaxies. We note that increasing this mass limit by a factor of ten does not influence our results, either qualitatively or quantitatively. All random rotations are applied prior to the mass cut in order to avoid problems in cases where a central galaxy below the limiting mass has satellites above it. Coloured lines indicate different sets of rotations, while the thick, black line shows the average of these. There is clearly a significant dip around $r \approx 2\,h^{-1}\,\mathrm{Mpc}$, with a depth of 2 per cent. This is due to the disruption of the alignment between haloes and surrounding structure. Note that the scatter is extremely low, due to the large number of objects (in fact, the uncertainty at large scales is dominated by the errors due to our approximate calculation of the correlation). Neglecting the orientation of haloes when populating them with galaxies will therefore have a modest, but significant, effect on the derived correlation function.

The ellipsoidal shape of the haloes, and the fact that the galaxy distribution follows this shape, is a more significant factor when modelling the galaxy distribution. Figure 2 shows the result of applying independent rotations, which sphericalize the galaxy distributions within haloes. This sub-

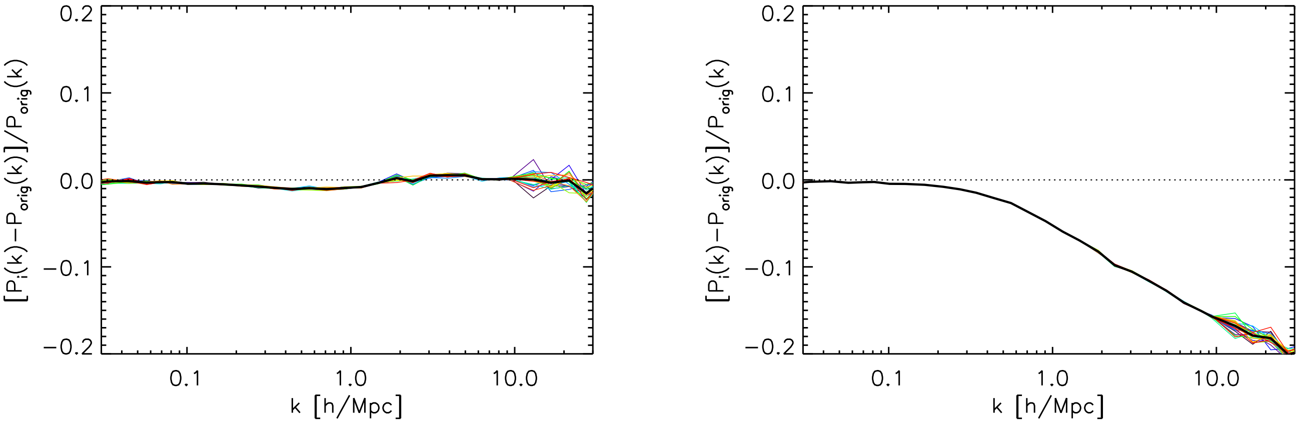

Figure 3. Same as Figures 1 and 2, but now for the fractional differences in the galaxy power spectrum versus the wave number k. *Left:* Result when testing for alignment. Again a weak but systematic signal of a few per cent can be seen, now between $k \approx 0.1\,h\,\mathrm{Mpc}^{-1}$ and $k \approx 2\,h\,\mathrm{Mpc}^{-1}$. *Right:* Result when testing for ellipticity. A monotonic decline in power sets in at $k \approx 0.1\,h\,\mathrm{Mpc}^{-1}$, reaching roughly 20 per cent at $k = 30\,h\,\mathrm{Mpc}^{-1}$, matching the result found in Figure 2. This again demonstrates the importance of taking the ellipsoidal shape of the galaxy distribution within haloes into account.

stantially suppresses correlations for $r \lesssim 2\,h^{-1}\,\mathrm{Mpc}$, with a ~ 20 per cent effect on the smallest scales probed here. The ellipsoidal shape of the galaxy distribution within haloes significantly reduces the typical separations of pairs within them. This is compensated by a $1-2$ per cent stronger correlation around $r \approx 3.5\,h^{-1}\,\mathrm{Mpc}$. We conclude that models that assume spherical profiles for the distribution of galaxies within haloes will underestimate the galaxy correlation function by up to ~ 20 per cent, depending on the smallest scale considered. Note that the scatter is even smaller than before on all scales, which is due to the increased number of degrees of freedom here.

One might worry that the necessarily artificial treatment of orphan, or “type 2”, galaxies in the galaxy formation models of G11 influences our result. G11 already showed that the inclusion of the orphans is critical if the radial distribution of galaxies within rich clusters in the Millennium Simulation is to agree both with observations and with the much higher-resolution MS-II. We have investigated effects on our analysis by repeating it with these galaxies removed, reducing our sample size by ~ 24 per cent and spoiling the relatively good agreement of its small-scale correlation with observation. This removal significantly amplifies the signal found for the effects of alignment. This is because the orphan galaxies are primarily located near halo centres. Once they are removed, galaxies that do contribute to the alignment signal receive more weight. Orphan removal also changes the signal found for the effects of ellipticity, modestly boosting it down to $r \approx 0.1\,h^{-1}\,\mathrm{Mpc}$, after which the signal begins to change sign. As a further check that the distribution of orphans in the simulation is realistic, we have examined the shapes of the galaxy distributions of massive haloes (specifically, $14 < \log_{10}(M_{\mathrm{FoF}}/[\,h^{-1}\,\mathrm{M}_{\odot}]) < 14.5$) in the MS and MS-II, again using G11’s galaxy catalogues and considering only galaxies with stellar masses $M_* > 10^9\,h^{-1}\,\mathrm{M}_{\odot}$. The better mass resolution of the MS-II results in far fewer orphans in this mass range, and consequently the positions of galaxies in MS-II are determined more accurately. Nevertheless, the shapes of the galaxy distributions agree very well, thus implying that the distribution of orphans in the MS is consistent with the distribution of similar, but unstripped, galaxies in the MS-II. We also found that these shapes agree very well with those of the dark matter haloes themselves (see Bett et al. 2007). A more detailed discussion of the shapes is beyond the scope of this paper.

Finally, for completeness, we have compared the galaxy-galaxy power spectra of the rotated and unrotated samples. The results are shown in Figure 3. Three foldings in total were used to calculate the power spectra over the full range shown, each with a fold factor of six (i.e. each folding maps the particle distribution to 1/216th of the volume). The power spectra were re-binned logarithmically to resemble the bins used for the galaxy correlation functions, and to reduce noise. Shot noise, which dominates the power for $k \gtrsim 10\,h\,\mathrm{Mpc}^{-1}$, was subtracted. The left-hand figure shows the fractional differences that result from applying bodily rotations. Just as for the correlation function, there is a weak but clear dip of $1-2$ per cent present which reflects the alignment of haloes with surrounding structure. As expected, the right-hand figure shows a much stronger decrease in power, up to 20 per cent on the smallest scales considered. This again demonstrates the importance of taking the ellipsoidal distribution of galaxies within FoF groups into account in, for example, models that use that use the full shape of the power spectrum to extract cosmological parameters.

Our results differ from those found by Smith & Watts (2005). Like ourselves, they find that the scale at which the contribution from alignments to the power spectrum is maximal is $\sim 0.5\,h\,\mathrm{Mpc}^{-1}$, but they show that the relative contribution of alignments is strongly model-dependent, varying from 10^{-12} to 10 per cent. Furthermore, they find that when haloes are assumed to be spherical, the power is higher than when they are ellipsoidal by up to 5 per cent. Not only is the effect we find significantly stronger and increasing towards smaller scales up to at least $k = 30\,h\,\mathrm{Mpc}^{-1}$, but its sign is opposite. We attribute these differences to the fact that in both models explored by Smith & Watts (2005), the radially averaged density profiles are not conserved when transforming the haloes from spherical to triaxial, making a comparison with our own results difficult.

4 SUMMARY

We have investigated the effects of the alignment of haloes with larger-scale structure and of halo ellipticity on the galaxy correlation function, using the Millennium Simulations (Springel et al. 2005, Boylan-Kolchin et al. 2009) and the galaxy formation models of Guo et al. (2011). By rotating satellite galaxies in FoF groups around their central galaxies, either coherently for each halo or independently for each satellite, and then comparing the correlation function of the resulting galaxy distribution to the original one, we were able to quantify the importance of taking halo alignment and non-sphericity into account. Galaxies with stellar masses $M_* > 10^9\,h^{-1}\,\mathrm{M}_\odot$ were considered in our analysis, though we note that increasing this mass limit by a factor of ten does not influence our results, either qualitatively or quantitatively. Our findings can be summarized as follows:

- The effects on the galaxy correlation function of the alignment of haloes with larger-scale structure are small. The main effect of disrupting this alignment is a 2 per cent reduction in correlation amplitude around $r \approx 1.8\,h^{-1}\,\mathrm{Mpc}$, with minor effects of at most 1 per cent at smaller scales.
- The ellipsoidal shapes of the galaxy distributions have a much stronger influence on galaxy correlations. By sphericalizing the galaxy distribution within haloes (i.e. randomizing the angular positions of satellites while keeping the distance from the central galaxy fixed), the correlation function is raised by up to 2 per cent around $r \approx 3.5\,h^{-1}\,\mathrm{Mpc}$, but greatly reduced for $r \lesssim 1.5\,h^{-1}\,\mathrm{Mpc}$, by up to ~ 20 per cent on the smallest scale probed, $r = 30\,h^{-1}\,\mathrm{kpc}$.

We have carried out a similar analysis on the galaxy power spectrum, and found matching results. By using the plane-parallel approximation and ignoring evolution, we have also checked that comparable results are obtained for the redshift-space correlation function. Models that assume a spherically symmetric profile for the galaxy distribution, such as HOD models, will therefore significantly underestimate galaxy correlations and power spectra on sub-Mpc scales.

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