The Virgo consortium: simulations of dark matter and galaxy clustering

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Abstract. We report on work in progress by the Virgo consortium, a collaboration set up to carry out large simulations of the formation of galaxies and large-scale structure exploiting the latest generation of parallel supercomputers. We show results of $256^3$ particle N-body simulations of the clustering evolution of dark matter in four cold dark matter models with different cosmological parameters. The high resolution and large volume of these simulations allows us to determine reliably the mass autocorrelation function for pair separations in the range $40h^{-1}$kpc to $20h^{-1}$Mpc. Comparison of these with the observed galaxy correlation function shows that for any of these models to be viable, the distribution of galaxies must be biased relative to the distribution of mass in a non-trivial, scale-dependent fashion. In particular, low $\Omega_0$ models require the galaxies to be more weakly clustered than the mass at small and intermediate pair separations. Simulations which include the evolution of gas show that cold gas knots form with approximately the abundance expected on theoretical grounds, although a few excessively massive objects grow near the centres of rich clusters. The locations where these cold gas...
knots form are, in general, biased relative to the distribution of mass in a scale-dependent way. Some of these biases have the required sign but they are, for the most part, weaker than is necessary for agreement with observations. The antibias present in our low Ω_0 N-body/SPH simulation appears to be related to the merging and disruption of galaxies in rich clusters.

1. Introduction

Understanding the relationship between the distribution of dark matter and the distribution of visible galaxies is one of the central problems of modern cosmology. Theoretically, the problem of calculating the statistical properties of the mass distribution in a given cosmological model (and here we will consider only hierarchical clustering models) consists primarily of understanding the gravitational dynamics of collisionless dark matter, as the baryonic component contributes only a small fraction of the total mass density. The gravitational evolution of dark matter universes has been extensively investigated using N-body simulations (for a review see Frenk 1991) and analytic approximations such as the Press & Schechter (1974) formalism and its extensions (Bower 1992, Bond et al. 1991) or second order perturbation theory (Bouchet et al. 1992, Bernardeau 1994).

With the exception of gravitational lensing studies, a subject still in its infancy, the only information we have on the properties of the underlying mass field, comes indirectly through studies of the baryonic component of the Universe, primarily galaxies, but also X-ray emitting gas in clusters and groups. Our lack of understanding of how the properties of the matter we can observe are related to the properties of the underlying mass field is a major obstacle in assessing the validity of theoretical models of structure formation. With the simplest possible assumption, that light traces mass (at least above some scale larger than that of galaxies where baryons dominate), hierarchical clustering theories do lead to model universes which superficially resemble our own. There are, however, many disagreements of detail with observations and there is much debate on how to remove these either by a suitable choice of cosmological parameters, by varying the assumptions about the nature of the dark matter or by arguing that the observed baryons are biased tracers of the mass.

A way out of this impasse is to try and predict the behaviour of baryonic matter from first principles. Unfortunately, the dissipative physics that govern the evolution of gas and the formation of stars makes this an exceedingly complex problem. One approach is to describe the behaviour of baryons within a merging hierarchy of dark matter halos using simple rules based on analytic or heuristic considerations. Such semianalytic modelling has proved quite successful in explaining some of the observed properties of galaxies (e.g. White and Frenk 1991; Kauffman et al. 1993; Cole et al. 1994). The more direct approach, which is allied to N-body simulations of the dark matter, is to try and calculate numerically the hydrodynamic evolution of baryons, using heuristic rules for describing processes associated with star formation. This approach requires formidable computing power which is only now becoming available (Cen & Os-
triker 1996, Katz et al. 1992, Evrard, Summers and Davis 1994, Frenk et al. 1996)

The Virgo consortium was formed with the aim of exploiting the latest generation of parallel supercomputers in order to address the problem of calculating the coupled evolution of dark matter and gas in the expanding universe. This kind of work represents a relatively new frontier where the very choice of numerical techniques and input physics is still very much an issue. Ultimately, it may prove possible to make reliable and testable predictions of, for example, the abundance and clustering pattern of galaxies expected in specific cosmologies. Here we give a short progress report on our programme. In section 2 we provide a very brief description of our numerical code and its current input physics. In section 3 we discuss results from large N-body simulations which reveal the kind of relationship required between the clustering of galaxies and dark matter in a selection of popular cosmological models. In section 4 we present preliminary results of two large N-body/gasdynamic simulations which begin to address the extent to which these requirements are met in practice. This work is ongoing and we refrain from drawing any strong conclusions at present.

2. The Code

Our current working code is based on “Hydra,” a code developed by Couchman, Thomas and Pearce (1995) and parallelized by Pearce et al. (1995). Gravity is treated using the adaptive P$^3$M technique and gas dynamics are treated using “Smooth Particle Hydrodynamics” (SPH). The smallest mesh refinements, placed on the regions of strongest clustering, are farmed out to individual processors. Larger refinements and the base level grid are run in parallel across all the processors. For a typical dark matter only run with $256^3$ particles, we use a $512^3$ grid as the base mesh and the code is run on 256 processors.

Although our code can treat the effects of a photoionizing background and, through a simple heuristic model, the effects of star formation and feedback, the gas simulations described below follow only the evolution of gas subject to radiative cooling and shocks. All our simulations have been carried out on Cray-T3Ds at the Edinburgh Parallel Supercomputer Centre and at the Max-Planck Rechen Zentrum in Garching.

3. Dark Matter Simulations

We have carried out a set of very large N-body simulations of cold dark matter universes with four different choices of cosmological parameters. With the exception of a $200^3$ particle open model, each simulation followed the evolution of $256^3$ particles in a computational box of $239.5h^{-1}$Mpc on side. (Here and below $h$ denotes Hubble’s constant in units of $100$ km/s/Mpc). The gravitational softening was typically $20–30h^{-1}$kpc. In all cases, the initial fluctuation amplitude was set by requiring that the model should reproduce the observed abundance of rich clusters at the present day. This was accomplished by setting, $\sigma_8$, the present day linear rms fluctuation on spheres of radius $8h^{-1}$Mpc, to the values recommended by White, Efstathiou & Frenk (1993) and Eke, Cole & Frenk (1996).
Figure 1. The mass autocorrelation function in 4 different cosmologies. The dashed lines show $\xi(r)$ at different redshifts as indicated in the figure legend. Baugh's (1996) estimates of the observed galaxy correlation function, based on the APM galaxy survey, are also shown: the solid curve assumes no evolution in the comoving clustering pattern, while the dotted curve assumes linear evolution on all scales. Error bars are shown only for the first estimate but they are similar for both. The lower plot in each panel gives the square root of the ratio of the observed galaxy correlation function to the predicted mass correlation function at $z=0$. This is the scale dependent bias required for each model to match observations.
Figure 1 shows mass autocorrelation functions, $\xi(r)$, at several epochs in all four simulations. Proceeding anticlockwise from the top left panel, the models plotted are: “standard” CDM (SCDM with $\Omega = 1$, $h = 0.5$, $\sigma_8 = 0.61$); “Lambda” CDM ($\Lambda$CDM with $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$, $h = 0.7$, $\sigma_8 = 0.9$); “Open” CDM (OCDM with $\Omega_0 = 0.3$, $h = 0.21$, $\sigma_8 = 0.85$); and “Taur” CDM ($\tau$CDM with $\Omega = 1.0$, $h = 0.5$, $\sigma_8 = 0.61$ and the same power spectrum shape as $\Lambda$CDM and OCDM). Because of the high resolution and large volume of these simulations the autocorrelation function is reliably determined over a large range of scales. The shape of $\xi(r)$ is broadly similar in all the models: it is relatively shallow on small scales, becomes increasingly steep and has an inflection point at $\xi \approx 1$. The SCDM case shows the steepest drop at pair separations $\sim 10h^{-1}\text{Mpc}$.

Also plotted in Figure 1 are estimates of the autocorrelation function of galaxies as inferred by Baugh (1996) from the angular correlation function of the APM galaxy survey (Maddox et al. 1990) and a model for the evolution of $\xi_{\text{gal}}(r)$. The solid curve with error bars shows the estimate assuming no evolution of clustering in comoving coordinates while the dotted curve shows the estimate assuming linear evolution of clustering on all scales. (The statistical errors are similar in both cases). Except in the OCDM case, $\xi(r)$ always falls below the galaxy data on very small scales. In the two $\Omega = 1$ models, the mass correlation function matches the galaxy data out to pair separations $\sim 1h^{-1}\text{Mpc}$ and then falls below them. In the low $\Omega_0$ cases, on the other hand, $\xi(r)$ rises above the galaxy data out to pair separations of a few $h^{-1}\text{Mpc}$ and then closely follows $\xi_{\text{gal}}(r)$ before falling slightly below it at the largest pair separations.

The lower box in each panel shows the square root of the ratio of the galaxy correlation function to the mass correlation function. This is the bias in the galaxy distribution that would be required for each model to match the observed strength of galaxy clustering. In all cases, the bias function is scale dependent. In the $\Omega = 1$ models, it is approximately unity at small and intermediate pair separation before rising steeply at large separations (particularly for the SCDM model). In our low $\Omega_0$ models, the bias falls below unity over a large range of pair separations indicating the need for a substantial negative bias or antibias.

Our analysis demonstrates that for the models under discussion to be viable a non-trivial relationship must exist between the distributions of galaxies and mass. These dark matter only simulations cannot be used to decide if such biases are plausible since this requires modelling the process of galaxy formation. In the next section we discuss our first attempts to address this problem.

4. Gas Simulations

We have carried out two N-body/SPH simulations that follow the coupled evolution of gas and dark matter in the SCDM and $\Lambda$CDM cosmologies discussed in the preceding section. (Because of a programming error the value of $\sigma_8$ in the $\Lambda$CDM model was set to 1.4 instead of the desired value of 0.9). Each species is represented by 2 million particles. The gas is allowed to cool radiatively according to the cooling function for a fully ionized plasma with half-solar metallicity. Experimentation shows that efficient cooling on galactic scales requires a gas particle mass of no more than $2 \times 10^9M_\odot$. We adopt the value of the baryon density, $\Omega_b$, implied by nucleosynthesis considerations: $\Omega_b h^2 = 0.015$ (Copi et
The simulations start at redshift $z = 25$ in the SCDM model and $z = 50$ in the ΛCDM model. Structure in the dark matter builds up in the familiar hierarchical fashion. The gas is able to cool radiatively into the evolving population of dark matter halos. There it settles into cold knots of size comparable to the gravitational softening length, $\sim 20$ kpc. These cold knots we identify with “galaxies.” At the present epoch, the number of galaxies with more than 20 gas particles is 1200 for SCDM and 1800 for ΛCDM. In Figure 2 we plot the baryonic mass function in the two models. The number densities decline at the low mass end due to resolution effects. Above the resolution limit, the number densities fall off with mass approximately as a power law, with perhaps an indication of a high mass cutoff.

One way to check whether these mass functions are correct, i.e. whether they are the expected outcome of the input physics, is to compare them with the results of the semianalytic models mentioned in Section 1. These can be tailored to include the same physics as the simulations, a mass resolution limit and gas subject only to shock heating and radiative cooling. The mass functions predicted by the appropriately modified version of the semianalytic model of Cole et al. (1994) are plotted in Figure 2 (Baugh, private communication). A mass resolution corresponding to 20 SPH particles has been assumed and results are shown for two gas metallicities, primordial (dotted line) and half-solar (dashed line). At the low mass end, the semianalytic calculation predicts many more “galaxies” than formed in the simulations. This indicates that the effective
mass resolution of the simulations is closer to 100 SPH particle masses than to 20. Indeed, beyond about $10^{11} M_\odot$, the agreement between the numerical and semianalytic results is good, particularly in view of the fact that there are no adjustable parameters in this comparison. At the high mass end both simulations, but particularly the ΛCDM model, produce too many objects. These very massive “galaxies” occur predominantly in the cores of rich clusters. Thus the simulations seem to suffer from an “overmerging” problem similar to that seen in the simulations of Frenk et al. (1996). This problem affects only a small fraction of the mass: the total amount of cold gas in the models and in the semianalytic models is very similar.

Autocorrelation functions for both galaxies and mass in our two simulations are shown in Figure 3. We split the galaxy samples into two halves, “heavy” and “light” galaxies with a cutoff mass of $M_{\text{gas}} = 6 \times 10^{10} h^{-1} M_\odot$ in the SCDM model and $M_{\text{gas}} = 1.3 \times 10^{11} h^{-1} M_\odot$ in the ΛCDM model. Apart from a moderate effect in the SCDM case at separations $\leq 1 h^{-1} \text{Mpc}$, there is little mass segregation when the sample is split in this way. The galaxy correlation functions are compared with the mass correlation function in the “bias” plots shown in the lower part of each panel. In the SCDM case the correlation functions of both heavy and light galaxies are positively biased relative to the mass on scales less than a few hundred $h^{-1} \text{kpc}$ and larger than about $2 h^{-1} \text{Mpc}$. By
contrast, in the ΛCDM case, galaxies of both types are antibiased over most of the distance range considered but they closely trace the mass at separations $\gtrsim 3h^{-1}\text{Mpc}$. The observed galaxy correlation function, reproduced from Figure 1, is shown as a dotted line in Figure 3. (For clarity we plot only the “no evolution” estimate). Although the various bias effects seen in the simulations seem to have the correct sign, they are, for the most part, weaker than required to account for the observations. We note, however, that our adopted value of $\sigma_8$ in the ΛCDM model was erroneously set too high and this might well have weakened the biases present in this model.

The weaker clustering of the galaxy distribution compared to the mass in the ΛCDM model is intriguing. This is the first time that such an effect has been seen in a cosmological simulation. A clue to its cause is provided by comparing the (number weighted) galaxy correlation function of Figure 3 with the galaxy-mass weighted correlation function. This comparison is carried out in Figure 4 and shows that the antibias is replaced by a positive bias when galaxies are weighted by their mass rather than equally. This suggests that the antibias
present in the galaxy distribution is related to the merging and disruption of galaxies in rich clusters which produces very massive objects at their centres. We are currently carrying out a series of tests to examine this issue in detail.

Whilst the physics in our dark matter simulations are well understood and the results are reliable, the same cannot yet be said of our dark matter plus gas simulations. We are continuing the analysis of these and related simulations in an effort to better understand the numerics and physics in a regime not previously explored. In particular, we stress that the galaxy correlation functions are very sensitive to the distribution of galaxies in the cores of rich clusters. The formation of excessively massive galaxies in these cores suggests that firm conclusions regarding biases in the galaxy distribution will have to await a better understanding of the processes at work in these extreme environments.

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