Structural properties of Dark Matter Halos

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Abstract. Using the results of a high mass resolution \((256^3\) particles) N-body simulation of a cluster-forming region, we study the statistic \(\sigma_v - M\) for low mass halos \((M < 10^{12} M_\odot)\), and we compare it with three theoretical models. At the final redshift halos are well described by the Truncated Isothermal Sphere model recently introduced by Shapiro, Iliev & Raga (1999). We speculate that this is a consequence of the action of tidal fields on galaxy formation within clusters.

1. Introduction

The study of the properties of halos produced in N-body simulations is of central importance to semianalytical modelling of galaxy formation and evolution within clusters. During the past four years, most attention has been paid to one out of the many possible statistics which could characterize the halo population, namely the density profile (Navarro, Frenk & White 1996; Tormen, Bouchet & White, 1997; Moore et al., 1999; Jing & Suto, 1999). However, it is difficult to determine reliably the density profile of numerical dark matter halos containing less than \(\approx 10^5\) particles: and in modern high resolution, parallel N-body cosmological simulations, there are typically not so many rich halos which are not formed by “overmerged” material in the center of clusters. In fact, all the work in the above mentioned papers where the density profiles are studied has been performed on halos extracted from some simulations and “re-simulated” at higher mass and spatial resolution. This allows one to study in detail at most a dozen of halos, but its is difficult to perform with this technique an analysis spanning a wide range of the possible halos’ parameters range. On the other hand, numerical simulations typically produce a lot of halos with \(\approx 10^1 - 10^4\) particles, which carry a significant dynamical information having been “pro-
cessed” by the gravitational field of the region where they form. It could be wise to try to use this statistical information to try to discriminate among different models of structure formation. Unfortunately we do not have a complete physical understanding of the gravitational instabilities which drive a halo (and particularly a numerical halo from an intrinsically spatially and temporally discrete experiment as a N-body simulation is) toward a (almost) relaxed state, so we must adopt models to interpret the results of numerical simulations. In this contribution we show that, given enough spatial and mass resolution, and choosing an appropriate statistics, it is possible to discriminate among different models of halo formation.

2. Models of collapse

We consider three models for gravitational collapse of halos: Singula Isothermal Sphere (SIS), the spherically-averaged peak-patch model by Bond & Myers (1996) and the Truncated Isothermal Spherical (TIS) model by Shapiro, Iliev & Raga (1999). The physical assumptions of the three models are significantly different. The SIS model is the simplest one, but also the most unrealistic: it predicts a singular density profile decaying $\rho_{SIS} \propto r^{-2}$. Total mass is infinite and density is everywhere nonzero (the system is not truncated).

The Bond & Myers model is based on a Monte Carlo approach named by their authors “peak-patch”. The underlying model is that of a collapse of a homogeneous spheroid, for which the equations of motion are exactly solvable. We consider here the spherically-averaged quantities computed from this model. The third and last is a recent class of isothermal, truncated models recently introduced by Shapiro et al. (1999). The main idea is to consider solutions of the Jeans’ equations for isothermal systems truncated at a finite radius. This is possible only if the shear gradient terms in these equations are not identically zero, for instance if an isotropic pressure term is present.

The relationship between 1-D velocity dispersion and mass in these three models is given by

$$\sigma_v = C_{SIS,TIS}(M_{12})^{1/3} (1 + z_{coll})^{1/2} h^{1/3}$$  \hspace{1cm} (1)

where: $C_{SIS} = 71.29$ and $C_{TIS} = 104.69$ (in km/sec), respectively, and $M_{12}$ is the mass in units of $10^{12}M_\odot$. For the Bond & Myers model the relationship is slightly different:

$$\sigma_v = 117.6 (M_{12})^{0.29} (1 + z_{coll})^{1/2} h^{1/3}$$  \hspace{1cm} (2)

(Bond & Myers 1996, eq. 4.4). Note that this latter relationship was obtained from a fit of Monte Carlo simulations for a range of mass much larger than the one we consider in this contribution (see next section).

3. Simulation and results

In order to test the models presented in the previous section, we will use the results from a N-body simulation we have recently performed. Initial conditions were picked up from the catalogue of simulated clusters by van Kampen & Katgert (1997): we choose a configuration which would produce a double cluster,
Figure 1. Virialization properties of the region around the DOUBLE cluster (see text). Gravitationally bound groups were identified by \textit{SKID}, using the same parameters as in the simulation and a standard percolation length $0.2r_{av}$. Only groups containing at least 50 particles were included in the final catalogue.

so we could study galaxy formation in a high shear environment. We then have run the same set of initial conditions with a higher mass and spatial resolution. The run was performed with $256^3$ particles using a parallel treecode (Becciani, Antonuccio-Delogu & Pagliaro, 1996). The softening length was fixed at $15 \, h^{-1} \text{kpc}$ (comoving). Although the simulation produces about a dozen of clusters, we will restrict our attention to the two major clusters, which are shown in Figure 3.

In order to study the virialization properties, it is important to adopt a physically motivated criterion to select the halos. This is because these properties are traced by gravitationally bound particles. Simple criteria (like friends-of-friends) do not distinguish particles on the base of their gravitational properties, but only on the base of their relative distance. Here we selected groups using \textit{SKID}, an open source software which produces catalogues of groups including only gravitationally bound particles (Stadel, Katz & Quinn, 1999). The only serious drawback concerning \textit{SKID} is that it is very slow. For this reason, we restricted our analysis to a $10^{3}h^{-3}\text{Mpc}^3$ region centered around the double cluster and a similar region centered around a single cluster. We denote these two regions as DOUBLE and SINGLE in the following.

DOUBLE and SINGLE contain approximately the same number of objects. Here we focus our attention on halos with masses in the range $10^{11} - 10^{12}M_{\odot}$, i.e. low-mass halos. These are the smallest objects we can reliably trace with the mass resolution and softening length we adopted. Within this mass range DOUBLE has 827 halos, while SINGLE has 757. From Figures 1 and 2 we can see that using our halo samples it is possible to discriminate among the three models outlined in the previous section. Both plots show that the TIS model offers a better description of the equilibrium properties of these halos. But notice also
that a fraction of halos in DOUBLE has velocity dispersions significantly smaller than the average. Tidal effects, which are much more pronounced in DOUBLE than in SINGLE, are responsible for this difference (Antonuccio-Delogu, Pagliaro & Becciani, 1999b).

4. Conclusion

The fact that the TIS model gives a better fit to the properties of low-mass virialized halos should not be surprising: it is possible to show that this reflects the action of the environmental tidal field on halo formation (Antonuccio-Delogu et al., 1999a). However, we have found that the actual profile of these halos is different from the Minimum Energy state suggested by Shapiro et al. (1999), and is rather more consistent with a tidally limited profile.

Before concluding, a few words about the consistency of the results of our work with the idea of the existence of a “universal” density profile. The TIS density profile differs significantly from either the Navarro et al. (1996) and the Moore et al. (1998) density profiles, because it flattens in the central region (i.e. it has a core). At the time we wrote this contribution, Jing & Suto (1999) submitted the results of a series of simulations which suggest a flattening of the inner 2% (in units of $r/r_{200}$) of the density profile in galaxy-sized halos. A similar flattening is not observed in their cluster-sized halos. The issue is then still an open one. All this seems to suggest that statistics based on virialization properties bear a smaller intrinsic uncertainty than the density profile, and are then more suitable to characterize the average statistical properties of halo populations.

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Figure 3. Final output of the simulation. The two regions from which low-mass galactic sized halos were extracted are centered around the two most massive clusters at (13,8) and (-18,3).