Dark Matter Halos Simulated with Million Particles

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Abstract

We report a series of high-resolution N-body simulations designed to examine the internal physical properties of dark matter halos. A total of fifteen halos, each represented by $\sim 1$ million particles within the virial radius, have been simulated covering the mass range of $2 \times 10^{12} \sim 5 \times 10^{14} h^{-1} M_\odot$. As the first application of these simulations, we have examined the density profiles of the halos. We found a clear systematic correlation between the halo mass and the slope of the density profile at one percent of the virial radius, in addition to the variations of the slope among halos of the similar mass. More specifically, the slope is $\sim -1.5$, $-1.3$, and $-1.1$ for galaxy, group, and cluster mass halos, respectively. Thus we conclude that the dark matter density profiles, especially in the inner region, are not universal.

1. Introduction

The internal structures within dark matter halos have important impact on galaxies and clusters formed within these halos. This is the reason for recent enormous interest in the innermost density profiles of the dark matter halos. From a set of halo simulations with $10^4$ particles, Navarro, Frenk & White (1997; NFW) concluded that the density profiles universally obey the NFW form $\rho(r) \propto r^{-1}(r + r_s)^{-2}$. It is yet unclear to which degree their results are affected by their selection criterion which is not well-defined, as questioned recently by Jing (1999). With a higher resolution of $\sim 10^6$ particles, Fukushige & Makino (1997) and Moore et al. (1998) found a steeper inner slope and argued that the slope might converge to a value about $-1.5$. However, Kravtsov et al.(1998), with a
resolution in between the above studies as the authors themselves claimed, found a shallower slope than the NFW one. Therefore, a consensus still needs to be reached about the inner density profile of the halos.

Motivated by these confusing results and the importance of studying other internal properties of the halos, e.g. substructures, we have selected 15 halos from a cosmological simulation and resimulated each halo with $\sim 10^6$ particles. We emphasize our selection of the halos is random (cf. NFW), in order to pin down selection effects introduced to the sample, thus in order to unbiasly study the internal properties of the dark matter halos.

2. Simulation procedure

We adopt the following two-step procedure. First we select 15 dark matter halos from our LCDM cosmological N-body simulation (Jing & Suto 1998), with five in each category which has a mass scale of clusters, groups, and galaxies respectively. These halos are resimulated typically with $2.2 \times 10^6$ particles, $\sim 1.5 \times 10^6$ fine particles for the central halo region and its nearby outskirts, and $\sim 0.7 \times 10^6$ coarse particles for outer region. About $(0.5 - 1) \times 10^6$ particles end up within the virial radius of each halo, making this sample as the largest sample of million particle halo simulations.

We developed a new algorithm, the nested-grid P$^3$M algorithm, to calculate the force with an accuracy around 0.1 percent. The force law is softened with the proper softening length about 0.004 the final virial radius. Each simulation has evolved 10,000 time steps by the leap-frog algorithm.

3. Density Profiles

As an important application, we have examined the radial density profiles (Jing & Suto 2000) which are plotted in Figure 1. The inner slope of the profiles, however, is generally steeper than the NFW value, $-1$, in agreement with the previous findings of Fukushige & Makino (1997) and Moore et al. (1998). We have fitted the profiles to $\rho(r) \propto r^{-\beta}(r + r_s)^{-3+\beta}$ with $\beta = 1.5$ (the solid lines) and $\beta = 1$ (NFW form; the dotted curves) for $0.01r_{200} \leq r \leq r_{200}$, where $r_{200}$ is the radius within which the spherical overdensity is $200\rho_{\text{crit}}(z = 0)$. The resulting concentration parameter $c$, defined as the $r_{200}/r_s$, is plotted in the left panel of Figure 2. This is the most accurate determination of the concentration parameter for the LCDM model. There exists a significant scatter among $c$ for similar mass (Jing, 1999), and a clear systematic dependence on halo mass (NFW, Moore et al. 1999).
Fig. 1. The density profiles of the simulated halos of galaxy (left), group (middle), and cluster (right) masses. The solid and dotted curves represent fits of $\beta = 1.5$ and $\beta = 1$ respectively. The vertical dashed lines indicate the force softening length. The open triangles in the right panel show the results of the cosmological simulation with the force softening marked by the long ticks at the bottom. The density value of each halo is multiplied by 1, $10^{-1}$, $10^{-2}$, $10^{-3}$ from top to bottom in each panel.

Our most important result is that the density profiles of the 4 galactic halos are all well fitted by $\beta = 1.5$, but those of the cluster halos are better fitted to the NFW form $\beta = 1$. This is in contrast with Moore et al. (1999) who concluded that both galactic and cluster halos have the inner density profile $\rho(r) \propto r^{-1.5}$, despite that they considered one cluster-mass halo alone. In fact, our current samples can address this question in a more statistical manner. CL1 has significant substructures, and the other three are nearly in equilibrium. Interestingly the density profiles of CL2 and CL3 are better fitted to the NFW form, and that of CL4 is in between the two forms. The density profiles of the group halos are in between the galactic and cluster halos, as expected. One is better fitted to the NFW form, whereas the other three follow the $\beta = 1.5$ form.

4. Conclusion and Discussion

We have presented the first study which simulates fifteen dark halos with about a million particles. This enables us to address the profile of the halos with unprecedented accuracy and statistical reliability. While qualitative aspects of our
Fig. 2. Left panel: the concentration parameters for each halo for $\beta = 1.5$ (filled circles) and for $\beta = 1$ (crosses). Numbers labeling each symbol correspond to the halo ID. Right panel: Power-law index of the inner region $(0.007 < r/r_{200} < 0.02)$ as a function of the halo mass. The upper and lower dotted curves bound the current analytical predictions (see Jing & Suto 2000 for a discussion).

Results are not inconsistent with those reported by Moore et al. (1999), our larger sample of halos provides convincing evidence that the form of the density profiles is not universal; instead it depends on halo mass. Since mass and formation epoch are linked in hierarchical models, the mass dependence may reflect an underlying link to the age of the halo. Older galactic halos more closely follow the $\beta = 1.5$ form while younger cluster halos have shallower inner density profiles fitted better by the NFW form.

Y.P.J. gratefully acknowledges a JSPS fellowship. Numerical computations were carried out on VPP300/16R and VX/4R at ADAC, NAOJ.

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