Evolution of Mass Distribution in CDM Halos

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Abstract. On the basis of a new convergence study of high-resolution N-body simulations, my colleagues and I now agree that the Navarro, Frenk, & White (1996) density profile $\rho_{\text{NFW}}(r) \propto r^{-1}(r + r_s)^{-2}$ is a good representation of typical dark matter halos of galactic mass. Comparing simulations of the same halo with numbers of particles ranging from $\sim 10^3$ to $\sim 10^6$, we have also shown that $r_s$, the radius where the log-slope is -2, can be determined accurately for halos with as few as $\sim 10^3$ particles. Based on a study of thousands of halos at many redshifts in an Adaptive Refinement Tree (ART) simulation of a cosmological volume in a $\Lambda$CDM cosmology, we have found that the concentration $c_{\text{vir}} \equiv R_{\text{vir}}/r_s$ has a log-normal distribution, with $1\sigma \Delta(\log c_{\text{vir}}) = 0.18$ at a given mass, corresponding to a scatter in maximum rotation velocities of $\Delta V_{\text{max}}/V_{\text{max}} = 0.12$. The average concentration declines with redshift at fixed mass as $c_{\text{vir}}(z) \propto (1 + z)^{-1}$. This may have important implications for galaxy rotation curves. Finally, we have found that the velocity function determined from galaxy luminosity functions plus luminosity-velocity relations agrees with the predictions from our $\Lambda$CDM simulations. But we also note that the very limited evolution with redshift of the velocity function predicted by $\Lambda$CDM conflicts with the data that is becoming available on the number density of bright galaxies unless there is significant evolution of the luminosity-velocity relation at $z > 1$.

1. Introduction

In this talk, I review some of the recent work by my collaborators (especially my former PhD student James Bullock) and me on the distribution of dark matter in galaxy-size halos and its evolution with redshift. I summarize results from several recent papers, in particular Bullock et al. (1999), Gonzalez et al. (2000), Sigad et al. (2000), Klypin et al. (2000), and Bullock et al. (2000). Avishai Dekel in his talk summarized related work by our group on the distribution of angular momentum in dark matter halos.

2. New results on the centers of dark matter halos

The ART code (Kravtsov, Klypin, & Khokhlov 1997) starts with a uniform grid treated with a Particle-Mesh algorithm, but refines all high-density regions using an automated refinement mechanism, with the time-step correspondingly
reduced. Extensive new tests of the ART code and comparison with other simulation codes are presented in Kravtsov (1999) and Knebe et al. (2000). In an earlier paper, Kravtsov et al. (1998) (discussed also in Primack et al. 1999), we analyzed ART simulations which resolved dozens of halos in small volumes for CDM, CHDM, and ΛCDM cosmologies. We concluded that the central density behavior is ρ ∝ r−γ, with γ typically ∼ 0.3 but ranging from about 0 to 1 for different halos. There we used results from ART simulations with a maximum formal dynamic range of $256 \times 2^6 = 16,384$, corresponding to a best formal resolution (size of the smallest refinement mesh cell) of $l_{\text{mesh}} \sim 0.5 \, h^{-1} \, \text{kpc}$, and we used only results for $\geq 2l_{\text{mesh}}$. This was because the convergence study that we described in that paper showed that for a fixed mass resolution the halo density profiles converged at $2l_{\text{mesh}}$ as we increased the force resolution.

For reliable results at the centers of dark matter halos it is also necessary to consider the effects of mass resolution. We have now done a more careful analysis of the convergence by simulating the same galaxy-mass halo with increasing numbers of particles. Our highest resolution runs achieved a formal spatial dynamical range of $2^{17} = 131,072$; the simulation was run with 500,000 steps at the highest level of refinement. Here we concentrated on the ΛCDM cosmology. We used a new version of the ART code with particles of various masses, so that we could put the lowest-mass particles in the region of the box containing the halo we were interested in and higher mass particles farther away. Our results show that there is no change in the simulated density profile as we increase the number of particles by a very large factor, down to a radius of at least 4 times the formal force resolution and containing at least 200 simulation particles. We find that $\rho_{NFW}(r)$ is a good fit to our highest resolution halos, although we show that several other popular analytic formulas also give good fits. In particular, the NFW formula is a good (better than 10%) fit to our halos down to 0.01 of the virial radius, which corresponds to $\sim 1\, h^{-1} \, \text{kpc}$ for the dwarf and LSB galaxies that are often compared to model predictions. It is hardly possible to measure rotation curves of such galaxies at smaller radii, and even if one could do so there are various physical effects that would make it difficult to interpret the results in terms of a density profile. Note that, although the log-slope of the NFW density profile is -1 in the limit as $r \to 0$, at 0.01 of the virial radius the log-slope is considerably steeper. For simulated halos the actual density profiles have features that deviate from smooth fitting formulas such as NFW, and at least some of these features appear to reflect the merging history of the halos.

Based on our new convergence study, we no longer trust the results reported in Kravtsov et al. (1998) concerning the very centers of halos. In particular, our results concerning the shallow central slopes depended on trusting our simulations between 2 and 4 times the formal resolution. However, all the results in Kravtsov et al. (1998) at radii greater than 4 times the formal resolution should still be valid, including the scatter in profile shapes and the agreement between the $V_{\text{max}}$ vs. $r_{\text{max}}$ relations of simulated dark halos and those of dark-matter-dominated dwarf and LSB galaxies. However, since the HI data on some of these galaxies was affected by beam-smearing (van den Bosch et al. 2000) and Hα data is now available for some of them (Swaters et al. 2000, Swaters & van den Bosch 2000; cf. contributions by Swaters and van den Bosch to these proceedings), it would be worthwhile to repeat this analysis.
Figure 1. (a) Convergence test for $c_{\text{vir}}$ evolution and scatter. Shown is a comparison of $M_{\text{vir}} = 3 \times 10^{11} h^{-1} M_\odot$ haloes simulated using our main simulation (thick lines) and a second simulation with 8 times the mass resolution (thin lines). The solid lines and errors reflect the median and Poisson uncertainty respectively. The dashed lines reflect the estimated intrinsic scatter. There is no evidence for significant deviations in either the measured median or scatter as the mass resolution is increased. (b) Concentration as a function of redshift for distinct halos of a fixed mass, $M_{\text{vir}} = 0.5 - 1.0 \times 10^{12} h^{-1} M_\odot$. The median (heavy solid line) and intrinsic 68% spread (dashed line) are shown. The behavior predicted by the NFW97 model is marked. Our revised model (available at www.astronomy.ohio-state.edu/~james/CVIR/ parts.html) for the median and spread for $8 \times 10^{11} h^{-1} M_\odot$ halos (thin solid lines) reproduces the results from the simulations rather well.

The new Hα data resolves much of the concern (e.g., Flores & Primack 1994) with rotation curves of dark-matter-dominated galaxies contradicting the cuspy halos from CDM simulations. The main related concern about too many small satellite halos compared to the number of observed satellite galaxies in the local group has been most convincingly addressed by the model of Bullock, Kravtsov, & Weinberg (2000), presented in two posters at this meeting. They show that only those small halos that have collapsed before the epoch of reionization will accrete gas and subsequently be able to produce stars, and that the numbers of the resulting small satellites — both those observed, and those subsequently accreted by the Milky Way — are in excellent agreement with observations.

3. Distribution and evolution of halo concentration

The convergence study of Klypin et al. (2000) shows that ART simulation halos with as few as $\sim 10^3$ particles can be used to get accurate values for the NFW parameter $r_s$ (where the log-slope of $\rho(r)$ is -2), as long as the NFW fit is restricted to begin at a sufficiently large radius. In Bullock et al. (1999), thousands of halos from a 60 $h^{-1}$ Mpc volume simulation of ΛCDM were analyzed at many redshifts to determine the distribution of halo concentration as a function of redshift. As
Fig. 1 (a) shows, a simulation with the same number of particles ($256^3$) in a 30 $h^{-1}$ Mpc box which was run to redshift $z = 1.7$ gave essentially identical results for the distribution of halo concentrations for halos of $(3 - 10) \times 10^{11} h^{-1} M_{\odot}$ at overlapping redshifts, despite the fact that identical mass halos had 8 times as many particles in the smaller box simulation.

We define the halo concentration as $c_{\text{vir}} \equiv R_{\text{vir}}/r_s$, where the virial radius $R_{\text{vir}}$ is defined as the radius within which the mean density is the virial overdensity $\Delta_{\text{vir}}$ times the average density at that redshift $\rho_{\text{ave}}$. The value of $\Delta_{\text{vir}}$, determined from the spherical top hat collapse approximation, depends on the cosmology and the redshift (see Bullock et al. 1999 for details). For the $\Omega_m = 0.3$ $\Lambda$CDM cosmology that we discuss, $\Delta_{\text{vir}} \approx 340$ at $z = 0$. (The definition above differs from that of NFW, who defined $c \equiv R_{200}/r_s$, where $R_{200}$ corresponds to $\Delta = 200$, appropriate for an Einstein-de Sitter cosmology.)

The dark matter halos in a fixed mass range at any redshift have approximately a log-normal distribution of concentrations (Jing 2000, Bullock et al. 1999). In Bullock et al. (1999) we present a simple analytic model for the concentration of dark matter halos. Like the model presented in Navarro, Frenk, & White (1997), it relates the concentration of a halo to the epoch when a certain fraction of the final mass in that halo had already collapsed; and like the NFW model, it correctly predicts the average halo concentration as a function of halo mass at redshift $z = 0$. But unlike the NFW model, it also correctly predicts the concentration as a function of redshift (see Fig. 1 (b)). In particular, it gives the $c_{\text{vir}} \propto (1 + z)^{-1}$ behavior that is evident in Fig. 1.

Our model also correctly accounts for the observed 1-$\sigma$ spread of concentrations (shown in Fig. 1 by the upper and lower dashed curves) in terms of the spread in halo formation epochs due to the Gaussian distribution of fluctuation amplitudes in CDM. The spread in halo concentrations has a large effect on galaxy rotation curve shapes, comparable to the effect of the well-known log-normal distribution of halo spin parameters $\lambda$. Frank van den Bosch (2000) showed, based on a semi-analytic model for galaxy formation including supernova feedback, that the spread in $\lambda$ mainly results in movement along the Tully-Fisher line, while the spread in concentration results in dispersion perpendicular to the TF relation. Remarkably, he found that the dispersion in CDM halo concentrations produces a TF dispersion that is consistent with the observed one.

In order to compare theoretical rotation curves to those of actual galaxies, it is necessary to take into account the effects on the dark matter halo of the dissipative collapse of the baryons that form the disk. In the papers (Blumenthal et al. 1986, Flores et al. 1993) that first discussed the effect of baryonic infall on galaxy rotation curves, we considered $z = 0$ galaxy disks to have formed at $z \sim 1$. Since in our study of CDM halo evolution we find that the concentration evolves $\propto (1 + z)^{-1}$, this would clearly result in lower concentration than if we used the $z = 0$ halo properties. This is a topic that requires further investigation before we can properly compare concentrations of observed galaxies with predictions of CDM models.
4. Galaxy velocity function from luminosity function and luminosity-velocity relations

A strength of CDM models is that it is possible to calculate the number density of halos with given properties. Although it is also possible to predict the number density of galaxies as a function of their luminosity by means of semi-analytic models (e.g., Somerville & Primack 1999), calculating luminosities of galaxies in CDM halos requires treatment of the poorly understood processes of gas cooling, star formation, and feedback, and many simplifications are necessary. The velocity function is a much simpler connection between theory and observation. Luminosity-velocity relations derived from observations — the Tully-Fisher and Faber-Jackson relations — allow one to construct approximate galaxy velocity functions from the observed galaxy luminosity functions. These are approximate since it is necessary to average over galaxy inclination for spiral galaxies, and for surveys in which the morphologies of galaxies were not determined it is necessary to make the approximation that all galaxies are spiral galaxies. However, in Gonzalez et al. (2000) we showed that the resulting uncertainty in the number density of galaxies with rotation velocity $\sim 200$ km s$^{-1}$ is only about a factor of 2. We found that the observational number density determined this way agrees well with that predicted in ΛCDM with $\Omega_m = 0.3$ if we don’t take into account the effect of baryonic infall, although it is perhaps a bit low when we do take this into account. New surveys, in particular the Sloan Digital Sky Survey, will determine the luminosity function much more accurately, and it will be important to measure the corresponding Tully-Fisher relation and compare the resulting velocity function to the predictions of cosmological models.

The fact that the luminosity-velocity relations work so well in the nearby universe raises the question whether they will continue to hold at higher redshift. In a recent paper (Bullock et al. 2000, based in part on the detailed analysis of ΛCDM velocity functions in Sigad et al. 2000), we point out that in the observationally favored ΛCDM cosmology with $\Omega_m = 0.3$ and $\sigma_8 = 1$, the number density of halos with maximum circular velocity $V_{\text{max}} = 200$ km s$^{-1}$ increases only by about 30% between redshift 0 and 3, and then declines back to the local value by $z = 5$. If the luminosity-velocity relations continue to hold at these higher redshifts, the implication is that the comoving number density of bright galaxies should increase. This appears to contradict the data from the Northern Hubble Deep Field (Dickinson 2000), which shows a dramatic decrease in the number of bright galaxies above redshift $z \sim 1.4$. So this suggests that the luminosity-velocity relations may change or perhaps even become stochastic at higher redshifts. The Keck DEEP survey will attempt to measure the internal velocities of $\sim 60,000$ galaxies at $0.7 \leq z \leq 1.5$, which should allow a direct test of this. Understanding the evolution of the luminosity-velocity relations may perhaps clarify their physical origin.

There is a more dramatic increase with redshift in the number density of halos with virial velocity of $200$ km s$^{-1}$, but the decrease in concentration with increasing redshift compensates for this and results in much less increase in the number density at fixed $V_{\text{max}}$. The number density of halos with $V_{\text{max}} = 200$ km s$^{-1}$ also increases out to $z \sim 2$ in open or Einstein-de Sitter CDM. Note that halos with fixed $V_{\text{max}}$ have decreasing mass at higher redshift.
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