RevMexAA (Serie de Conferencias), **18**, 4–7 (2003)

The eighth Mexico-Texas Conference on Astrophysics: Energetics of Cosmic Plasmas (Mexico City, Mexico, 31 October - November 2, 2002)
Editors: Mauricio Reyes-Ruiz & Enrique Vazquez-Semadeni

DENSITY PROFILES OF DARK HALOS FROM THEIR MASS ACCRETION HISTORIES

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RESUMEN

Utilizando la historia universal de acreción de masa derivada de simulaciones de formación de halos en el modelo de materia oscura fría (CDM) analizamos la formación y crecimiento de un halo individual. Derivamos el perfil de densidad utilizando tres aproximaciones de menor grado sucesivamente: equilibrio, órbitas radiales, y una aproximación de fluido. En el modelo de equilibrio, el perfil de densidad se ajusta bien por un perfil de NFW o por un perfil de Moore sobre un rango limitado de radios y factores de escala. En el modelo de órbitas radiales encontramos un perfil mas empinado que el de NFW, con una pendiente logarítmica en la parte interior cercana a -2, consistente con un sistema no colisional puramente radial. En la aproximación de fluido encontramos concordancia con los perfiles de Moore y NFW para radios resueltos por las simulaciones de N-cuerpos ($r/r_{200} \geq 0.01$) y una evolución de los parámetros de concentración casi idéntica a la que se encuentra en dichas simulaciones. Por lo tanto, la evolución de la estructura de halos cosmológicos se entiende mejor como un efecto de la tasa de acrecion variante en el tiempo sobre un fluido no colisional, isotropico y de distribución suave.

ABSTRACT

We use the universal mass accretion history recently reported for simulations of halo formation in the cold dark matter model (CDM) to analyze the formation and growth of a single halo. We derive the time-dependent density profile three different ways, based upon three approximations of successively greater realism: equilibrium, radial orbits, and a fluid approximation. For the equilibrium model, the density profile is well-fit by either an NFW or Moore profile over a limited range of radii and scale factors. For the radial orbit model, we find profiles which are generally steeper than the NFW profile, with an inner logarithmic slope approaching -2, consistent with a purely radial collisionless system. In the fluid approximation, we find good agreement with the NFW and Moore profiles for radii resolved by N-body simulations ($r/r_{200} \geq 0.01$), and an evolution of concentration parameter nearly identical to that found in N-body simulations. The evolving structure of cosmological halos is therefore best understood as the effect of a time-varying rate of mass infall on a smoothly distributed, isotropic, collisionless fluid.

Key Words: **COSMOLOGY: THEORY — DARK MATTER — GALAXIES: FORMATION — LARGE-SCALE STRUCTURE OF UNIVERSE**

1. INTRODUCTION

Current understanding of dark matter halos relies upon N-body simulations of collisionless cold dark matter (CDM) with Gaussian-random-noise initial conditions. Two "universal" profiles bracket the results ; (Navarro, Frenk, & White 1997; Moore et al. 1998). The NFW(Moore) profile has an inner density profile $\rho \propto r^{-1}(r^{-1.5})$. Wechsler et al. (2002) (WBPKD hereafter) found that the mass and concentration of individual N-body CDM halos grow over time according to simple universal formulae. In what follows, we attempt to explain this result.

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2. THREE DIFFERENT MODELS

We attempt to understand the form and evolution of dark matter halos with three spherically-symmetric models; equilibrium, radial orbits, and an isotropic fluid. Each model assumes that the mass $M_{\rm vir}$ within an overdensity $\delta_{\rm vir}$ follows the relation given by WBPKD

$$M_{\rm vir}(a) = M_\infty \exp\left[-S a_{\rm c}/a\right], \qquad (1)$$

where a_c is the scale factor at collapse and S is the logarithmic mass accretion rate $d(\ln M_{\rm vir})/d(\ln a)$ when $a = a_c$. Such a relation is claimed to be a good fit to the evolution of halos of different masses and formation epochs. As in WBPKD, we have chosen

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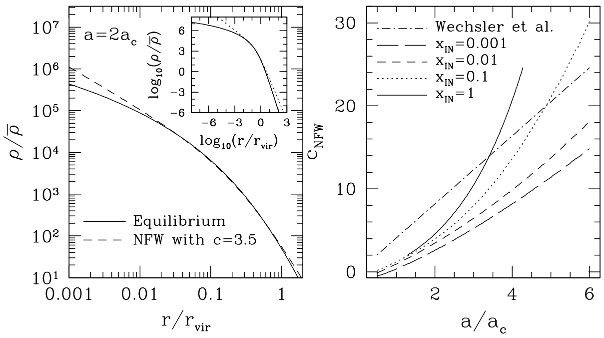

Fig. 1. (Left) Density profile from equilibrium model along with best-fitting NFW profile for this profile at present. Inset in upper-right shows same over much larger range. (Right) Evolution of NFW concentration parameter in the equilibrium model. Different line types indicate different ranges $x_{\rm in} < x < 1$, within which halo was fit to an NFW profile, where $x \equiv r/r_{\rm vir}$,$r_{\rm vir} \equiv r_{200}$.

$S = 2$ and $\delta_{\rm vir} = 200$, so that the halo has a mass M_{200} and radius r_{200}. We have found an initial perturbation profile consistent with equation (1),

$$\frac{\delta M}{M} \equiv \frac{M - \overline{M}}{\overline{M}} = \delta_{\rm i} \ln \left[\frac{M}{bM_\infty}\right], \tag{2}$$

where $\delta_{\rm i}$ depends on the initial scale factor $a_{\rm i}$ and $\delta_{\rm vir}$, and $\overline{M}$ is the unperturbed mass. The free parameter b is unity in the absence of pressure or shell crossing inside of $r_{\rm vir}$.

2.1. *Equilibrium*

In the simplest model, we have made the assumption of complete equilibrium inside the halo, so that

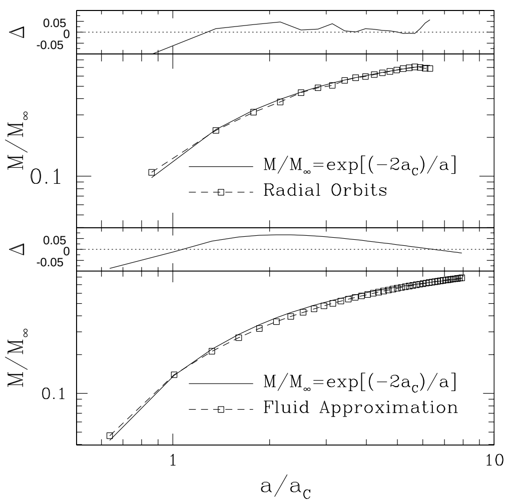

Fig. 2. Evolution of mass for the radial orbits (top) and fluid approximation (bottom) simulations. Shown above each are the fractional deviations $\Delta \equiv (M_{\rm exact} - M)/M$.

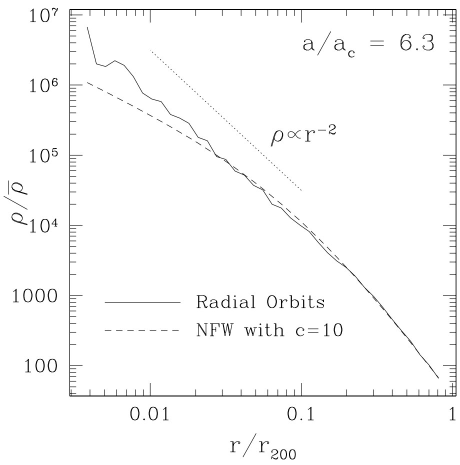

Fig. 3. Density profile at the end of the radial orbit simulation.

the velocity is zero for $r < r_{\rm vir} \equiv r_{200}$. The mass of the halo is given by

$$M_{\rm vir}(a) = \frac{4\pi}{3}\delta_{\rm vir}\overline{\rho} r_{\rm vir}^3, \tag{3}$$

where $\overline{\rho}$ is the mean density at that epoch. Mass continuity implies the density $\rho_{\rm vir}$ just inside the virial radius is

$$\frac{dM_{\rm vir}}{da} = 4\pi\rho_{\rm vir} r_{\rm vir}^2 \frac{dr_{\rm vir}}{da}. \tag{4}$$

Differentiating equation (3) and combining with equations (1) and (4) yields

$$\frac{\rho_{\rm vir}}{\rho_0} = \delta_{\rm vir} a^{-3}\left[1 + \frac{3a}{Sa_c}\right]^{-1}, \tag{5}$$

where ρ_0 is the mean background density at $a = 1$. The virial radius is given by

$$\frac{r_{\rm vir}}{r_0} = a \exp\left[\frac{-Sa_c}{3}\left(\frac{1}{a} - 1\right)\right]. \tag{6}$$

Equations (5) and (6) are parametric in a, implying a radial density profile $\rho(r) = \rho_{\rm vir}(r_{\rm vir})$ which is frozen in place as matter crosses $r_{\rm vir}$. Taking the limit in which $a \to \infty$, the outer density profile approaches $\rho \propto r^{-4}$ at late times, consistent with finite mass, while the inner slope becomes asymptotically flat. The NFW profile is given by

$$\frac{\rho(x)}{\overline{\rho}} = \frac{\delta_{\rm vir} g(c)}{3x(1+cx)^2}, \tag{7}$$

where

$$g(c) = \frac{c^2}{\ln(1+c) - c/(1+c)}, \tag{8}$$

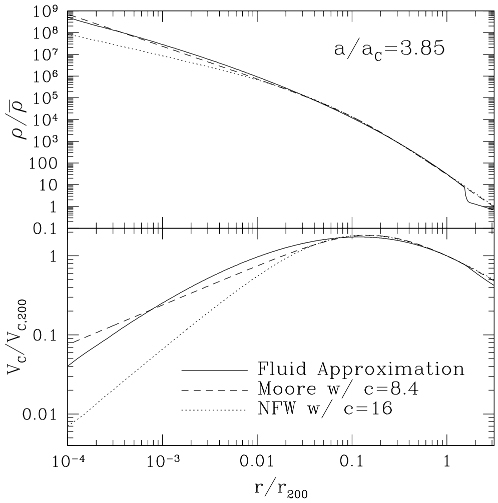

Fig. 4. (Top) Density profile at the end of the isotropic fluid calculation. (Bottom) Circular velocity profile.

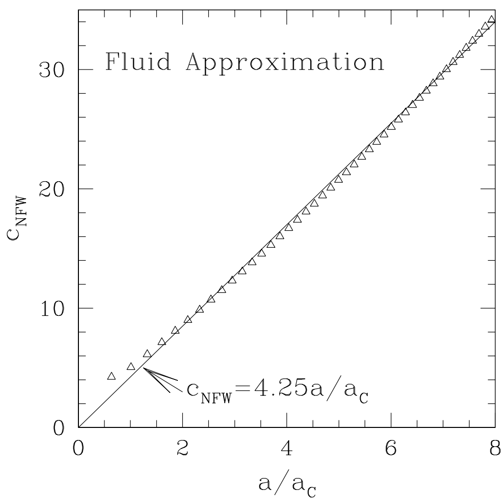

Fig. 5. Evolution of concentration parameter with scale factor in the isotropic fluid calculation.

and $x \equiv r/r_{\rm vir}$. Combining equations (5) and (7) with $x = 1$, yields an equation for the evolution of concentration with scale factor (see Fig. 1),

$$\frac{a}{a_c} = S\left[\frac{(1+c)^2}{g(c)} - \frac{1}{3}\right]. \qquad (9)$$

2.2. *Radial Orbits*

We use a finite-difference spherical mass shell code to follow the evolution of a small amplitude perturbation which is chosen so that the resulting virial mass will evolve according to equation (1) from an initial perturbation given by equation (2). The shell code has an inner reflecting core and the results presented here used 20,000 shells (see Figs. 2 and 3).

2.3. *Fluid Approximation*

The collisionless Boltzmann equation in spherical symmetry yields fluid conservation equations ($\gamma = 5/3$) when random motions are isotropic. Halos in N-body simulations have radially biased random motion, but the bias is small, especially in the center. This model is therefore a better approximation to halo formation in N-body simulations than one with purely radial motion. We use a 1-D, spherical, Lagrangian hydrodynamics code as in Thoul & Weinberg (1995), using 1,000 zones logarithmically spaced in mass (see Figs. 2, 4, and 5). The initial conditions were chosen in the same way as those for the radial orbit model (Eq. 2), with zero initial temperature.

3. RESULTS

- Equilibrium model does not reproduce linear evolution of concentration parameter with scale factor reported by WBPKD, but can be fit by an NFW profile over a limited range of radii and scale factors (Fig. 1).
- Mass evolution for a perturbation given by equation (2) is close to that of equation (1) (Fig. 2).
- The radial orbit model fails to reproduce the inner slope of the NFW profile, approaching $\rho \propto r^{-2}$ instead, consistent with the argument of Richstone & Tremaine (1984) (Fig. 3).
- Fluid approximation halo is well-fitted by NFW and Moore profiles for radii resolved by N-body simulations ($r/r_{200} \geq 0.01$) (Fig. 4).
- Evolution of NFW concentration parameter in the fluid approximation is a close match to that of WBPKD, with $c_{\rm NFW} = 4.25a/a_c$ a good fit (Fig. 5). WBPKD reported $c_{\rm NFW} = 4.1a/a_c$. Complicated merging process is not necessary in order to understand density profile evolution.

This work was supported in part by grants NASA ATP NAG5-10825 and NAG5-10826 and Texas Advanced Research Program 3658-0624-1999.

REFERENCES

Moore, B., Governato, F., Quinn, T., Stadel, J., & Lake, G. 1998, ApJ, 499, L5

Navarro, J.F., Frenk, C.S., & White S.D.M. 1997, ApJ, 490, 493

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Richstone, D.O. & Tremaine, S. 1984, ApJ, 286, 27
Thoul, A. A. & Weinberg, D.H. 1995, ApJ, 442, 480
Wechsler R.H., Bullock, J.S., Primack, J.R., Kravtsov, A.V., & Dekel, A. 2002, ApJ, 568, 52

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