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ON THE ORIGIN OF CUSPS IN DARK MATTER HALOS

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ABSTRACT

Observed cusps with density profiles $\rho \propto r^{-1}$ or shallower in the central regions of galaxies cannot be reproduced in the standard cold dark matter picture of hierarchical clustering. Previous claims to the contrary were based on simulations with relatively few particles and substantial softening. We present simulations with particle numbers 1 order of magnitude higher and essentially no softening, and we show that typical central density profiles are clearly steeper than $\rho \propto r^{-1}$. The observed shallower profiles may have formed through the smoothing effect of the spiral-in of central black holes in previous merger phases. In addition, we confirm the presence of a temperature inversion in the inner 5 kpc of massive galactic halos and illustrate its formation as a natural result of the merging of unequal progenitors.

Subject headings: cosmology: theory — dark matter — galaxies: formation — galaxies: kinematics and dynamics — methods: numerical

1. INTRODUCTION

Recent high-resolution ground-based and *Hubble Space Telescope* observations (Lauer et al. 1995) have revealed that elliptical galaxies do not have a constant-density core and that the densities continue to rise until the resolution limit. In faint elliptical galaxies, the density profile at the central region increases roughly as $\rho \propto r^{-2}$, and in bright elliptical galaxies it increases as $\rho \propto r^{-1}$ or shallower (Merritt & Friedman 1996).

Several simulations demonstrated that the dark matter halos formed through hierarchical clustering were not well approximated by isothermal spheres and were better fitted by a Hernquist model (Hernquist 1990) or similar models with $\rho \sim 1/r$ at the center (Dubinski & Carlberg 1991; Navarro, Frenk, & White 1996a, 1996b). In these simulations, halos have a power-law index that changes from around -1 to -3 or -4 as the radius increases. Recently, Moore (1994) and Flores & Primack (1994) have argued that the gently rising $\rho(r)$ curves of dwarf galaxies are inconsistent with an r^{-1} central cusp and therefore challenge the hypothesis of cold dark matter (CDM) halos.

However, whether the results of numerical simulations are physically valid or are numerical artifacts remains unclear for the following reasons. First, no physical mechanism has been presented so far for the formation of cusps found in simulations (White 1996). Second, since the mass resolution in these simulation was rather low, the central structure may have been affected by two-body relaxation effects (Quinlan 1996; Steinmetz & White 1996; Fukushige & Makino 1996). Third, the central structures of halos formed in these simulations are strongly affected by the potential softening used and show rapid change in the power index of $\rho(r)$ around a radius not much larger than the potential softening length.

In this Letter, we have been able to separate physically real effects from numerical artifacts, through N-body simulations of hierarchical clustering with a resolution far higher than those in previous work. The number of particles that we used ($N = 786{,}400$) is more than 10 times larger than those used in previous simulations ($N \sim 10{,}000$–$30{,}000$), and our softening is significantly smaller (§ 2).

Our results show that dark halos formed through hierarchical clustering typically exhibit an inwardly decreasing temperature structure in their inner regions, with a density cusp shallower than $\rho \propto r^{-2}$ but steeper than $\rho \propto r^{-1}$ (§ 3). We illustrate the origin of this behavior through an idealized merger simulation of different types of galaxies (§ 4), which enables us to give a physical explanation of temperature inversion (§ 5).

2. METHOD

Initial conditions were constructed following Dubinski & Carlberg (1991). We assigned initial positions and velocities to particles in a spherical region with a radius of 2 Mpc surrounding a density peak selected from a discrete realization of a standard CDM model ($H_0 = 50$ km s^{-1} Mpc^{-1} and $\Omega = 1$). The peak was chosen from a realization of the density contrast in an 8 Mpc box, using *COBE* normalization. The peaks were found by smoothing the density with a Gaussian filter of radius 0.75 Mpc.

We followed the evolution of a density peak through direct N-body simulation. We added the local Hubble flow and integrated the orbits directly in physical space, with $N = 786{,}400$, an individual particle mass of 4.0×10^6 $M_\odot$, and a Plummer softened potential with a length of $\varepsilon = 0.14$ kpc. We started the simulation at $z \sim 46$. We did not include tidal effects from outside our 2 Mpc sphere, since we are mainly interested in the core properties within 10 kpc, where tidal effects from outside the 2 Mpc scale are negligible.

We used a fourth-order Hermite integration scheme (Makino & Aarseth 1992) with an individual (hierarchical) time step algorithm (McMillan 1986; Makino 1991a).

For the force calculation, we used the GRAPE-4 (Taiji et al. 1996), a special-purpose computer designed to accelerate N-body simulations using a Hermite integrator and a hierarchical time step algorithm. The total system consists of 1692 pipeline processor chips dedicated to gravity calculation and has a peak performance of 1 Tflops. The calculation with $N = 786{,}400$ took about 180 CPU hr (5.7×10^9 particle steps) using 3/4 of the total system. The sustained speed of computation was 406 Gflops. Since the force calculations on GRAPE-4 are effectively of double-precision accuracy

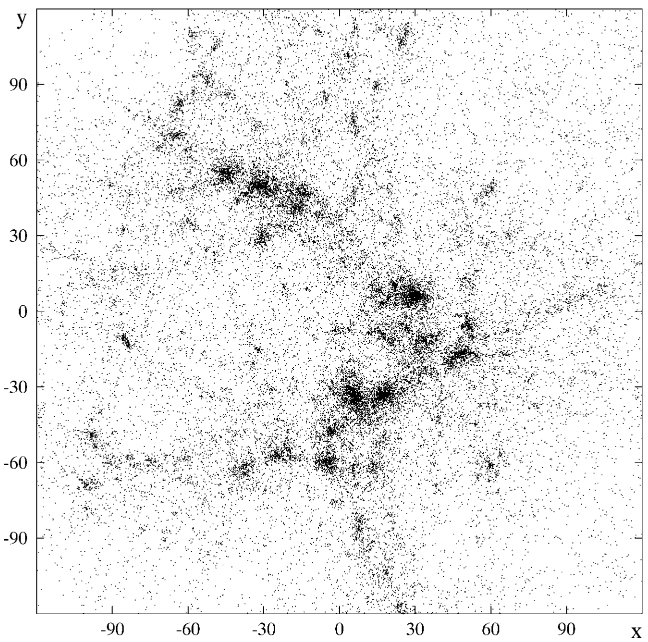

FIG. 1*a*

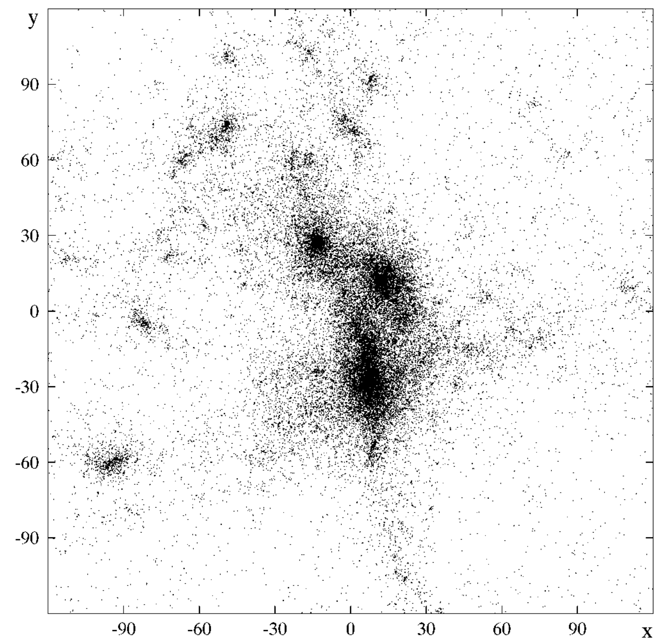

FIG. 1*b*

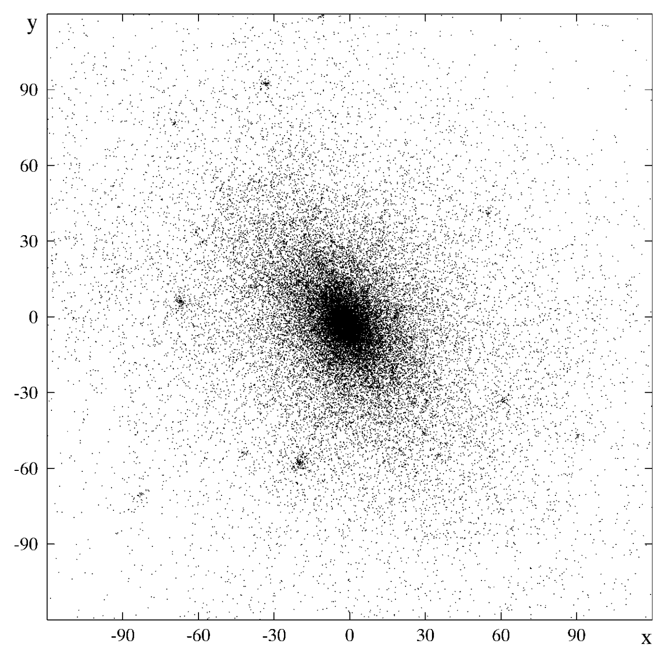

FIG. 1*c*

FIG. 1.—Snapshots of *N*-body simulation of hierarchical clustering at redshifts (*a*) $z = 8.7$, (*b*) 5.1, and (*c*) 1.8. The unit of length is 1 kpc.

(Makino et al. 1997), our simulations exhibit much higher accuracy both for force calculations and orbit integrations than previous simulations.

3. HIERARCHICAL CLUSTERING SIMULATIONS

Figure 1 shows the particle distributions in our simulation at the redshift $z =$ (*a*) 8.7, (*b*) 5.1, and (*c*) 1.8. Figure 2 shows the density and temperature structure of the halo at $z = 1.8$, well after most of the merging has already taken place (results at $z = 0$ are similar, but these earlier stages show even less effects of two-body relaxation). In Figure 2 we can see a clear temperature decrease toward the center within 5 kpc. This nonisothermal structure produces a density cusp shallower than $\rho \propto r^{-2}$. In our simulation, the structure outside 1 kpc is not affected by two-body relaxation after the formation of a large single halo at $z \sim 3$; only the central region within 1 kpc shows some expansion because of two-body relaxation effects.

The large potential softening employed in previous studies has produced spurious structures, which we have been able to reproduce, using additional simulations with larger softening,

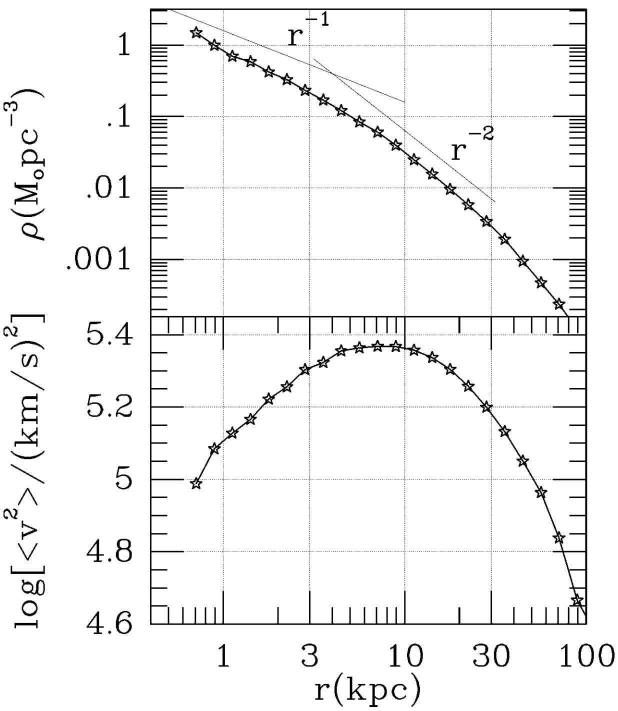

FIG. 2.—Density and temperature structures of the halo at $z = 1.8$ in the *N*-body simulation shown in Fig. 1. The position of the center of the halo was determined using potential minimum and averaged physical values over each spherical shell.

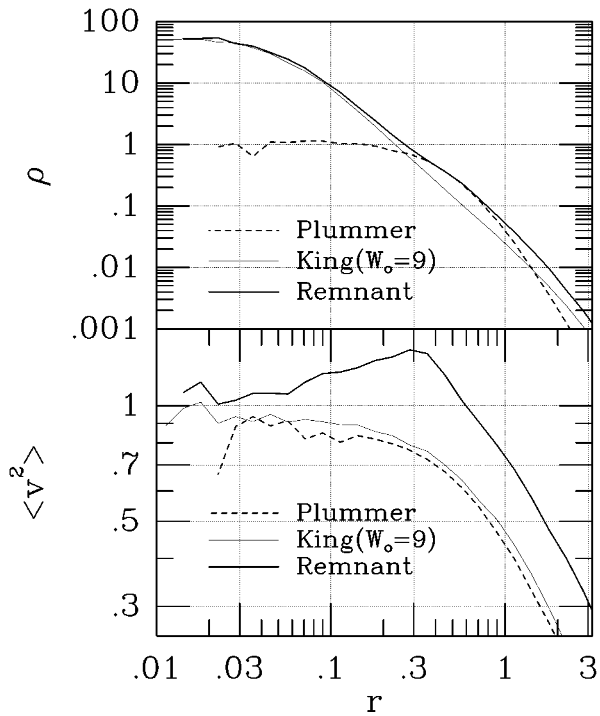

FIG. 3.—The density and temperature structures of the merger remnant formed by the merging of two equal-mass clusters with different central densities.

leading to a central temperature decrease within a region a few times larger than the softening radius. The potential softening tends to produce a flat core on the scale of the softening length. Thus, unless we use point-mass particles, we always see a tendency for the power index of the density profile to approach zero at a radius comparable to the softening radius.

After most of the merging has taken place, subsequent two-body relaxation effects due to small *N* values continue to lead to spurious changes in the central region. For example, a density cusp might evolve to a flat core through gravothermal expansion (Quinlan 1996; Fukushige & Makino 1996). In our simulation, the local two-body relaxation times at 1 and 5 kpc are 1.2×10^{10} and 2.3×10^{11} yr, respectively. Therefore, only the structure within 1 kpc is somewhat affected by two-body relaxation in our simulation. In simulations with $N \sim 10{,}000$ such as those reported by Dubinski & Carlberg (1991) and Navarro et al. (1996a, 1996b), the local relaxation time at 5 kpc was approximately 3.0×10^9 yr, implying that the effect of two-body relaxation completely dominated their results at that distance.

4. IDEALIZED MERGER SIMULATIONS

In order to illustrate the formation of temperature inversion after merging, we performed an idealized simulation in which we merged two equal-mass spherical halos with different central densities, a Plummer model, and a King model with central potential $W_0 = 9$. The result is shown in Figure 3. The central temperature inversion is striking.

The encounter between the halos is head on, starting from rest at an initial separation of $R = 5$ (in standard units with $M = G = -4E = 1$, where G is the gravitational constant and M and E are the total mass and the initial total energy of a halo; see Heggie & Mathieu 1986). The total number of particles is $N = 262{,}144$, and the softening length is 1/256. We used a Barnes-Hut tree code on GRAPE-4 (Makino 1991b) for the force calculations. The time step is shared and constant ($\Delta t = 1/512$).

In hierarchical clustering, temperature inversion takes place in the inner halos in a similar way. Figure 4 shows the evolution of temperature structure for the simulation of halo formation presented in § 3. We can see that the temperature of the outer halo regions increases faster than the temperature of the central halo regions.

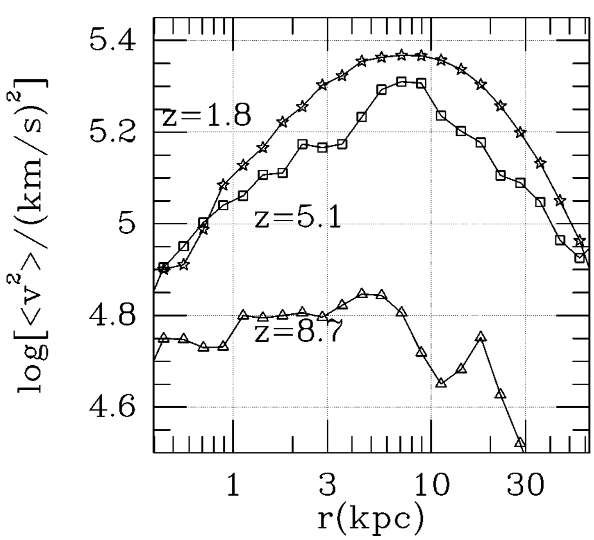

FIG. 4.—Evolution of temperature structures of the halo at $z = 8.7$ (*triangle*), 5.1 (*square*), and 1.8 (*star*) obtained by *N*-body simulation illustrated in Fig. 1. We made the temperature profile in the same way as in Fig. 2.

5. DISCUSSION

In this Letter, we have shown that dark halos formed through hierarchical clustering have a central density cusp shallower than $\rho \propto r^{-2}$ and a velocity dispersion that has a local minimum in the center, peaks at a distance of 5 ∼ 10 kpc from the center, and then drops again in the outer halo. We offer the following interpretations for the temperature and the density structures found.

The occurrence of the striking temperature inversion can be understood as follows. In bottom-up structure formation, as in CDM hierarchical clustering, a typical halo is formed through repeated merging of smaller subclumps. Each time this happens, the less concentrated clump tends to be disrupted by the tidal field of the more centrally concentrated clump. The dense core of the latter survives the merging process more or less intact and settles down at the center of merger remnant, with locally unchanged temperature. In contrast, the temperature of the merger remnant as a whole increases, since the specific binding energy of the merger remnant is almost always larger than that of its progenitors.

As a result, present-day halos tend to carry some memory of the temperature of their densest progenitor clump, which has set the temperature scale in the inner, and densest, regions. Since the bulk of the halo is affected more by subsequent mixing and heating, a central temperature inversion is naturally created. This formation process is evident, not only in our hierarchical clustering simulations, but also in our idealized simulation of a merger between two different halos, one with dense inner region and another one with a much flatter core.

The occurrence of steep density profiles, significantly steeper than $\rho \propto r^{-1}$, naturally follows from the same physical picture. According to our detailed *N*-body calculations, in a purely CDM scenario each final halo forms a repository for the small inner cores of the subclumps that have made up the final dark matter aggregate.

Comparing our results with observations, we conclude that the shallow cusps of large elliptical galaxies cannot have formed through the dissipationless processes that we have modeled here. Instead, we interpret the presence of density profiles shallower than $\rho \propto r^{-1}$ as strong evidence for the existence of central massive black holes, through the following mechanism. As an aftereffect of the merger of two black hole–containing galaxies, the spiral-in of those two massive black holes tends to smear out the central cusp that would have otherwise formed, as shown in detailed calculations of hierarchical merging of galaxies by Makino & Ebisuzaki (1996).

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