On the Origin of Cusps in Dark Matter Halos

Toshiyuki Fukushige and Junichiro Makino
Department of General Systems Studies,
College of Arts and Sciences, University of Tokyo,
3-8-1 Komaba, Meguro-ku, Tokyo 153, Japan
Email: fukushig@chianti.c.u-tokyo.ac.jp

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 (CDM) 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 an order of magnitude higher, and essentially no softening, and 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.

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 the densities continue to rise until the resolution limit. In faint ellipticals, the density profile at the central region increases roughly as $\rho \propto r^{-2}$, and in bright ellipticals it increases as $\rho \propto r^{-1}$ or shallower (Merritt and Friedman 1996).

Several simulations demonstrated that the dark matter halos formed through hierarchical clustering were not well approximated by isothermal spheres, and better fitted by a Hernquist model (Hernquist 1990) or similar models with $\rho \sim 1/r$ at the center (Dubinski and Carlberg 1991; Navarro, Frenk, and White 1996a, 1996b). In these simulations, halos have a power law index which changes from around -1 to -3 or -4 as the radius increases. Recently, Moore (1994) and Flores and Primack (1995) have argued that the gently rising $\rho(r)$ curves of dwarf galaxies are inconsistent with a r^{-1} central cusp, and therefore challenge the hypothesis of 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).

Secondly, 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 and White 1996, Fukushige and Makino 1996). Thirdly, 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 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 and Carlberg (1991). We assigned initial positions and velocities to particles in a spherical region with a radius of 2Mpc surrounding a density peak selected from a discrete realization of a standard CDM model ($H_o = 50$km/s/Mpc and $\Omega = 1$). The peak was chosen from a realization of the density contrast in an 8Mpc 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 $4.0 \times 10^6 M_\odot$, 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 2Mpc sphere, since we are mainly interested in the core properties within 10kpc, where tidal effects from outside 2Mpc scale are negligible.

We used a 4-th order Hermite integration scheme (Makino and Aarseth 1992) with individual (hierarchical) timestep 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 timestep 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 hours (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 (Makino et al. 1996), 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 mergings has already taken place (results at $z = 0$ are similar, but these earlier stages shows even less effects of two-body relaxation). In figure 2 we can see a clear temperature decrease toward the center within 5kpc. This non-isothermal 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, 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 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 and 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} years, respectively. Therefore, only the structure within 1kpc is somewhat affected by two-body relaxation in our simulation. In simulations with $N \sim 10,000$ such as reported by Dubinski and Carlberg (1991) and Navarro et al. (1996a, 1996b), the local relaxation time at 5kpc was $\sim 3.0 \times 10^9$ years, 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; cf. Heggie and Mathieu 1986). The total number of particles is $N = 262,144$ and the softening length is 1/256. We used Barnes-Hut tree code on GRAPE-4 (Makino 1991b) for the force calculations. The timestep 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 section 3. We can see that the temperature of the outer halo regions increases faster than the temperature of the central halo regions.

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 $5 \sim 10$ 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 ellipticals 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 and Ebisuzaki (1996).

Acknowledgement

We are grateful to Makoto Taiji, for his important contribution in developing the GRAPE-4, and to the referee, Piet Hut, for many helpful comments on the manuscript.

T.F. acknowledges financial support by JSPS. To generate initial condition, we used the COSMIC package developed by Edmund Bertschinger, to whom we express our thanks. This research was partially supported by the Grand-in-Aid for Specially Promoted Research (04102002) of The Ministry of Education, Science and Culture.

References

Dubinski, J., end Carlberg, R., 1991, ApJ, 378, 496

Fukushige, T., and Makino, J., 1996, in preparation.

Heggie, D. C., and Mathieu, R. D., 1986, in The Use of Supercomputer in Stellar Dynamics (ed. Hut, P., McMillan, S.) 233, (Springer-Verlag, Berlin)

Hernquist, L., 1990, ApJ, 356, 359

Lauer, T. R. et al., 1995, AJ, 110, 2622

Makino J. 1991a, PASJ, 43, 859

Makino J. 1991b, PASJ, 43, 621

Makino J. and Aarseth, S. J. 1992, PASJ, 44, 141

Makino, J., and Ebisuzaki, T., 1996, ApJ, 465, 527

Makino, J., Taiji, M, Ebisuzaki, T. and Sugimoto, D., 1996, submitted to ApJ.

McMillan, S. L. W., 1986, in The Use of Supercomputers in Stellar Dynamics, eds. S. L. W. McMillan, P. Hut (Springer, Berlin) p 156

Merritt, D., and Fridman, T., 1996, in Fresh Views of Elliptical Galaxies, eds. Buzzoni, A., Renzini, A. Serrano, A. (ASP conference Series Vol. 86)

Moore, B., 1994, Nature, 370, 629

Navarro, J. F., Frenk, C. S., and White, S. D. M., 1996a, ApJ, 462, 563

Navarro, J. F., Frenk, C. S., and White, S. D. M., 1996b, preprint (astro-ph/9611107)

Quinlan, G, D., 1996, preprint (astro-ph/9606182)

Steinmetz, M. H., and White, S. D. M., 1996, preprint (astro-ph/9609021)

Taiji, M., Makino, J., Fukushige, T., Ebisuzaki, T., and Sugimoto, D., 1996, in IAU Symposium 174, eds. Makino, J., Hut, P. (Kluwer Academic Press)

White, S. D. M. 1996, in Gravitational Dynamics, ed. Lahav, O., Terlevich, E., Terlevich, R. J., 121 (Cambridge University Press)

Figure 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 kilo parsec.

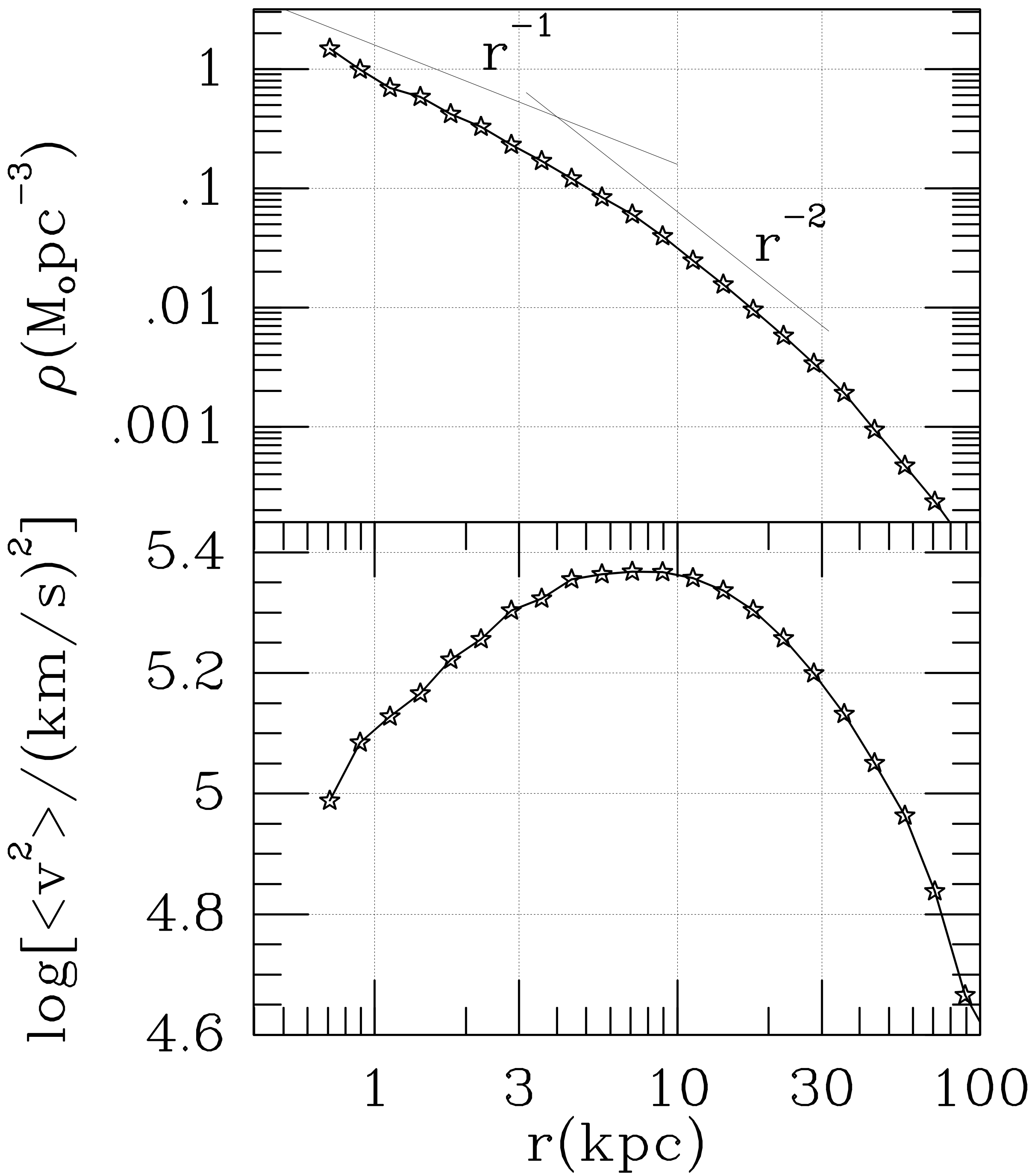

Figure 2: Density and temperature structures of the halo at $z = 1.8$ in the N-body simulation shown in Figure 1. The position of the center of the halo was determined using potential minimum and averaged physical values over each spherical shell.

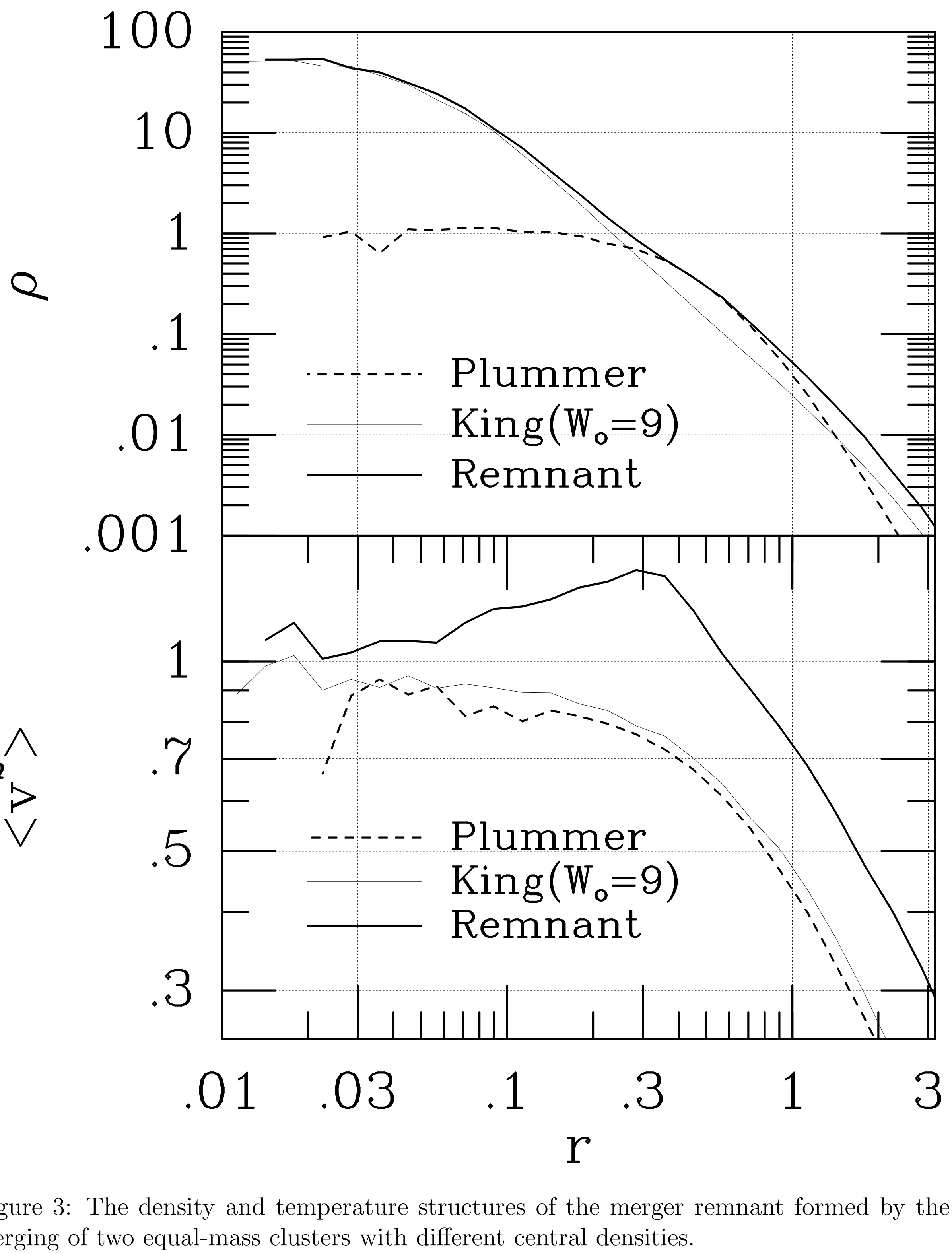

Figure 3: The density and temperature structures of the merger remnant formed by the merging of two equal-mass clusters with different central densities.

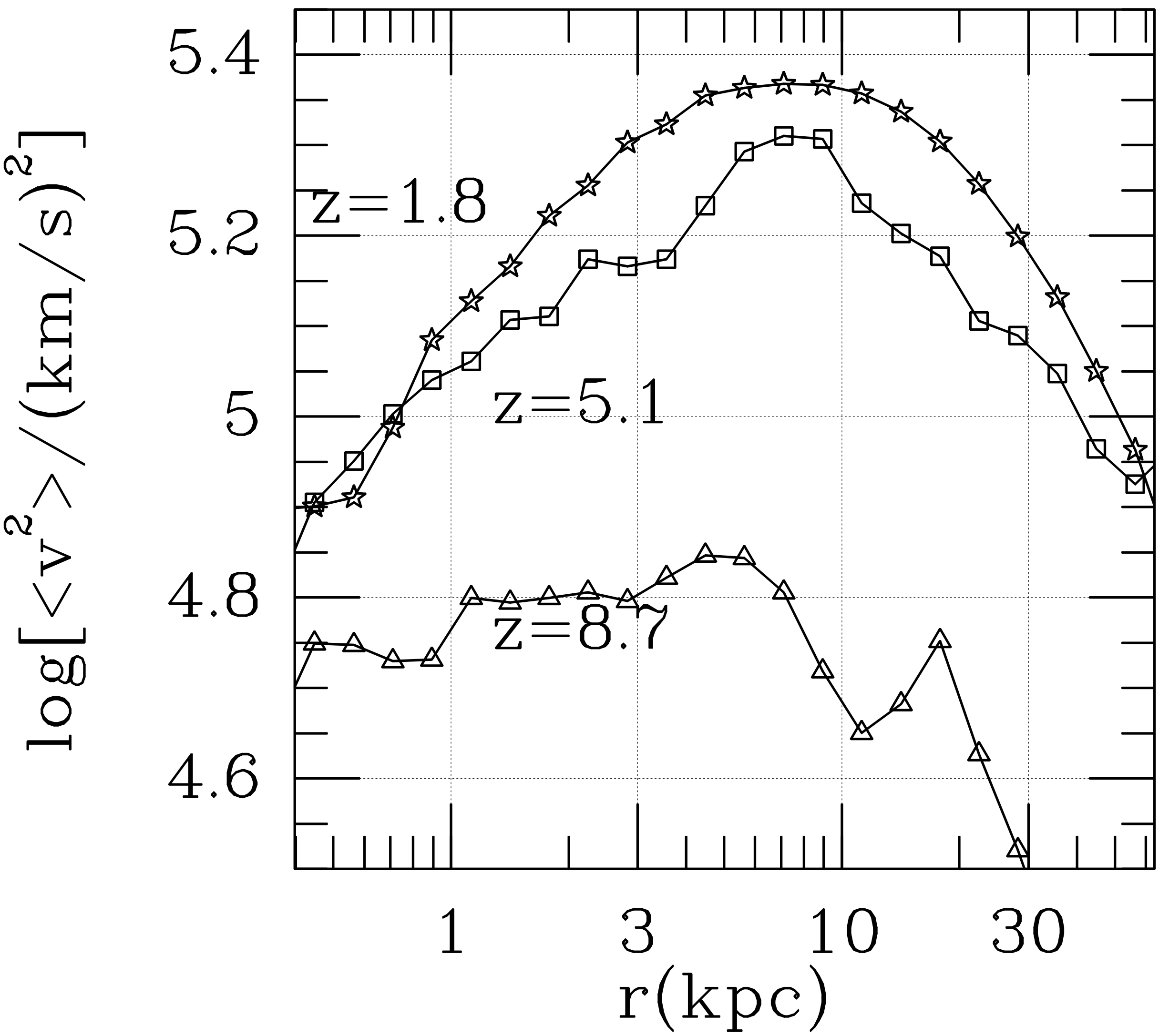

Figure 4: Evolution of temperature structures of the halo at $z = 8.7$(triangle), 5.1(square), and 1.8(star) obtained by N-body simulation illustrated in Figure 1. We made the temperature profile in the same way as in figure 2.