THE INFLUENCE OF BARYONS ON THE MASS DISTRIBUTION OF DARK MATTER HALOS

W.P. LIN\textsuperscript{1,4}, Y.P. JING\textsuperscript{1,4}, S. MAO\textsuperscript{2}, L. GAO\textsuperscript{2}, I.G. MCCARTHY\textsuperscript{3}

Abstract

Using a set of high-resolution \textit{N}-body/SPH cosmological simulations with identical initial conditions but run with different numerical setups, we investigate the influence of baryonic matter on the mass distribution of dark halos when radiative cooling is not included. We compare the concentration parameters of about 400 massive halos with virial mass from $10^{13}$ to $7.1 \times 10^{14} \hbar^{-1} M_{\odot}$. We find that the concentration parameters for the total mass and dark matter distributions in nonradiative simulations are on average larger by $\sim 3\%$ and $10\%$ than those in a pure dark matter simulation. Our results indicate that the total mass density profile is little affected by a hot gas component in the simulations. After carefully excluding the effects of resolutions and spurious two-body heating between dark matter (DM) and gas particles we conclude that the increase of the DM concentration parameters is due to interactions between baryons and DM. We demonstrate this with the aid of idealized simulations of two-body mergers. The results of individual halos simulated with different mass resolutions show that the gas profiles of densities, temperature and entropy are subjects of mass resolution of SPH particles. In particular, we find that in the inner parts of halos, as the SPH resolution increases the gas density becomes higher but both the entropy and temperature decrease.

subject headings: galaxies; halos – cosmology: theory – dark matter – methods: numerical

1. INTRODUCTION

One potential problem of the cold dark matter (CDM) cosmology is the mass distributions in the central region of clusters of galaxies. There is yet no consensus emerging from the observations. In general, simulations produce steep inner density profiles for DM halos (Navarro et al. 1997; Moore et al. 1998; Jing & Suto 2000), while observations of some clusters seem to prefer flat, core-like profiles (e.g., Tyson et al. 1998), and others prefer cusped profiles (e.g., Lewis et al. 2003; Buote & Lewis 2004; Pointecouteau et al. 2005).

Sand et al. (2004) show that the central DM profiles of clusters of galaxies have a slope of about $-0.5$, which is substantially flatter than the inner slope ($-1$) of the Navarro-Frenk-White (NFW) profile as found in CDM simulations. However, other authors argued that their interpretations are compromised by the assumption of sphericity (e.g., Bartelmann & Meneghetti 2004; Meneghetti et al. 2005; Dalal & Keeton 2003). Recent observations of strong gravitational lensing have shown that some clusters of galaxies have very high mass concentration parameters (e.g., Broadhurst et al. 2005) compared with the average value obtained in the DM simulations. The number of giant arcs predicted by \textit{N}-body simulations may also be somewhat too low to be compatible with observations (Li et al. 2005; but see Dalal et al. 2004; Hennawi et al. 2006; Horesh et al. 2005). It is unclear whether these “discrepancies” are serious. Hence, the systematics in theoretical predictions need to be explored, and the effect of baryons is one of these.

Baryons can cool via dissipative processes while DM is collisionless, and so their density evolutions may be quite different. Although the baryonic matter is only a modest fraction of the total mass (less than or equal to the universal baryon fraction of $\sim 16\%$, as revealed by the Wilkinson Microwave Anisotropy Probe [WMAP]; Spergel et al. 2003, 2006), it can nevertheless play a significant role in reshaping the density profiles of the DM halos. For example, the baryons that condense toward the center of DM halos can compress DM by adiabatic contraction (Blumenthal et al. 1986; Mo et al. 1998). This effect was confirmed in simulations with gas cooling where the DM density profiles appear steeper than those in the pure DM simulations (e.g., Pearce et al. 2000; Gnedin et al. 2004). Even for nonradiative gas simulations, several studies (Pearce et al. 1994; Navarro et al. 1995; Rasia et al. 2004; Jing et al. 2006) suggest that the mass density profiles of DM halos become steeper. Some analytic studies (e.g., Zhan & Knox 2004) often adopt DM profiles (such as the NFW profile) straight from DM-only simulations and do not take into account the modification of the DM profiles by baryons. In this paper, we explore the effects of baryons using high-resolution simulations with nonradiative gas. In this case, the interaction between the hot gas and DM is a well-defined problem, and hence our study sets a benchmark for the effects of baryons on the matter distribution when important (but more uncertain) star formation and feedback processes are incorporated. To do this, we perform a set of \textit{N}-body/SPH simulations with different mass and force resolutions and compare the results with those in a pure DM simulation. We will examine effects of resolutions and spurious two-body heatings between the gas and DM particles (Steinmetz & White 1997). The layout of this paper is as follows. In §2 we give an introduction of our simulations and methods; in §3 we present our main results. We examine the hypothesis of energy transfer from DM to gas in §4, and finish with a summary and discussion in §5.

2. THE SIMULATIONS AND METHODS

We use the massively parallel GADGET2 code (Springel et al. 2001; Springel 2005) to simulate structure forma-
tion. The code can follow a collisionless fluid with the $N$-body method, and an ideal gas by means of smoothed particle hydrodynamics (SPH). The GADGET2 implementation of SPH conserves energy and entropy (Springel & Hernquist 2002). The simulations were performed in a concordance cosmological model with the following parameters ($\Omega_m, \Omega_\Lambda, \Omega_b, \sigma_8, n, h$) = (0.268, 0.732, 0.044, 0.85, 1.071). Five simulations were run with the same initial condition in a cubic box of side-length 100 $h^{-1}$ Mpc (see Table 1 for details). A pure DM (PDM) simulation is used as a comparison for the simulations that include baryons. In the four simulations with gas, no radiative cooling is considered and the gas is treated as an ideal gas with an adiabatic index $\gamma = 5/3$.

The highest resolution simulation we performed is A4, which includes an equal number (512$^3$) of gas and DM particles. The simulation A1 has the lowest resolution, but it has the smallest softening length relative to the mean interparticle separation, about $\sim 1/80$ ($\sim 1/40$ for other simulations). A1 is used to check the effects of spurious large accelerations in close approaches between particles (the real mass distribution is inherently smooth and unable to generate large accelerations). In run A2, we double the softening length from A1 to check its effects. We also ran a simulation A3, in which gas and DM particles have comparable mass to study spurious two-body heating effects, which depend on the number of DM particles used (Steinmetz & White 1997). Two-body heating occurs when DM particles collide with gas particles, lose their kinetic energy to the gas components, and, as a result become more concentrated. This effect is cumulative in a cosmological simulation and may be particularly serious in simulations with low mass resolutions or for halos with a small number of particles. Thus it has been suggested that it is wise to use more DM particles than gas particles for cosmological simulations (Steinmetz & White 1997); the A3 run fulfills this requirement. Table 1 lists the number and mass of particles, and the softening length used in the simulations.

The simulations discussed above are all evolved from redshift $z = 120$ to the present epoch. Because the initial conditions are identical, one can match each well resolved halo on an one-to-one basis in different runs. Thus it is straightforward to select the massive mass halos at $z = 0$ and compare their radially averaged density profiles in different simulations. The NFW form (Navarro et al. 1997) is used to fit the halo density profiles. The NFW profile is given by $\rho(x) = \Delta \bar{\rho} f(c)/x(1+c)^2$, where $\Delta = 200$ is the overdensity, $\bar{\rho}$ is the mean universe mass density, $x = r/r_{200}$, $c$ is the concentration parameter defined as $c = r_{200}/r_s$, and $f(c) = c^3/(3\ln(1+c) - c/(1+c))$. Here $r_{200}$ is the virial radius within which the average mass density is 200 times the mean background density (not the critical density as used in some other studies), and $r_s$ is the scale radius.

The radii of the halos are divided in uniform logarithmic steps from $0.001r_{200}$ to $2r_{200}$. The number of particles and the average density in each bin are then computed. Note that when fitting the NFW profiles, we use only data between a minimum radius, $r_{\text{min}}$, and $r_{200}$. For runs A1, A2 and A4, the minimum fitting radius $r_{\text{min}}$ is 0.02$r_{200}$ (corresponding to a physical radius from 10.5 to 45 $h^{-1}$ kpc); for run A2 we use $r_{\text{min}} = 0.04r_{200}$ to match the larger force softening length. The $r_{\text{min}}$ value is chosen correspondingly for the PDM simulation. The best-fit parameters (including the concentration parameter $c$) are found by minimizing

$$\sum_i \left[ \log \rho(r_i) - \log \rho_{\text{NFW}}(r_i) \right]^2.$$  

Notice that when we fit the DM profiles in simulations with gas, we scaled the overdensity $\Delta$ by the DM mass fraction (0.84).

3. The Influence of Nonradiative Gas on Density Profiles

We choose a large number of massive halos (about 400) to statistically quantify the systematic influence of the hot gas on the matter distribution of halos. We only use those halos more massive than $10^{13} h^{-1} M_\odot$ (corresponding to $\sim 1.67 \times 10^4$ particles in the PDM simulation and $3.11 \times 10^4$ particles in run A4).

The concentration parameters for these halos in our highest resolution run, A4, versus those in the PDM simulation are shown in Figure 1. The left and right panels show the concentration parameters for the DM and total mass distributions, respectively. For the total mass distribution, the concentration parameter is increased only slightly (by about 3%), while the increase for the DM distribution is larger, at about 10%. The effects of baryons (without radiative cooling)-on the density profile appear to be modest.

To examine how the numerical setups affect the DM and total mass distributions, in Figure 2 we show the ratios of the concentration parameters in nonradiative gas simulations relative to the PDM simulation. The median values of this ratio

![FIG. 1.—Halo concentration parameters in the highest resolution run, A4, compared with those in the PDM simulation. In each panel, the filled circles and squares are for the DM and total mass, respectively. The solid lines indicate equality, while the dashed lines indicate the concentration parameters that are 10% (left) and 3% (right) higher than those in the PDM case.](image-url)
are plotted in five mass bins with equal numbers of halos, together with the vertical error bars showing the lower (25%) and upper (75%) quartiles in each bin. The ratios of the halo concentration parameters in runs A1 and A2 with those in the PDM run appear to show a systematic trend with mass for halos with $M \lesssim 3 \times 10^{13} h^{-1} M_\odot$. A1 and A2 both have 256$^3$ DM particles, a factor of 8 lower than A3 and A4. The inner halo profiles are less well resolved in A1 and A2. Thus, this poorer resolution results in the mass dependence and the higher median values of the ratio of the concentration parameter. The median values for the ratio of the DM in A1 and A2 are comparable with each other. For the A1 run, as a small softening length (relative to the mean inter-particle separation) was used, one can imagine that artificially large accelerations at close encounters may suppress structure formation at high redshift in this case, but apparently the effect has not accumulated significantly to the present epoch.

A3 and A4 have the same number of DM particles and force resolution; they only differ in the number of gas particles ($256^3$ vs. $512^3$). The third and fourth columns in Figure 2 show that A3 and A4 are in good agreement with each other. It appears to make little difference for the density profiles of halos whether an equal mass is used for DM and gas particles in simulations. Furthermore, for both the DM and total mass the ratios of their concentration parameters to those in the PDM simulation do not have significant dependence on the halo mass (especially for A4). The very weak mass dependence and larger scatter in run A3 may be due to the low mass resolution of the gas component. The consistency between A3 and A4 shows that the resolutions of A4 are sufficient for examining the influence of baryons on the density profiles for massive halos that are well resolved by a large number of particles.

The results we have shown so far are statistical; below we use two individual halos to see the changes in the halo profiles. Figure 3 shows the density profiles, $r^2 \rho(r)$, for two halos with mass of $7.08 \times 10^{14} M_\odot$ and $4.16 \times 10^{13} h^{-1} M_\odot$. The first halo is the most massive one in our simulation. It has a virial radius of $2.2h^{-1}$ Mpc and contains 1.3 million DM and 1.2 million gas particles in run A4, so it is well resolved. Figure 3 shows that in run A4, the DM and total mass distributions are slightly steeper than the DM distribution in the PDM run, between $0.02r_{200}$ and $0.12r_{200}$, making the concentration parameter larger. As expected, the distribution of gas is substantially more extended due to pressure that resists the gravitational collapse. This is also reflected in the baryon fraction as a function of radius: in the central region, the gas mass fraction is only about 10% at $R \sim 0.02r_{200}$ (and even smaller at smaller radii) while it approaches the universal baryon fraction close to the virial radius (see also Ascasibar et al. 2003). For the group-sized halo shown in the bottom panel of Figure 3 (other low-mass halos show similar behavior), all the simulations have roughly the same gas density profiles when $R \gtrsim 0.1r_{200}$, but there appears to be a weak trend for A4 to have a slightly lower gas density at intermediate radius ($r \sim 0.2r_{200}$) than A1 and A3. However, in the inner regions, the gas density distributions differ markedly: the highest resolution run, A4, has the highest gas density, while the lowest resolution run, A1, has the lowest values.

In Figure 4, we plot the temperature and entropy profiles for the two halos shown in Figure 3. The trend of the temperature as a function of radius is roughly the reverse of the trend for the density, i.e., A4 has the lowest temperature in the inner regions. This is because the gas pressure ($P \propto \rho T$) is well constrained by hydrostatic equilibrium (see Fig. 16 in Frenk et al. 1999). As one can see in the top panels, the temperature profiles exhibit a flat core toward the halo center, and drop off sharply toward the outer part of halo. These behaviors are similar to those found by previous studies (Loken et al. 2002; Ascasibar et al. 2003; Rasia et al. 2004) in spite of the higher mass and force resolutions in our simulations. Comparisons between different simulations also reveal that as the resolution increases, the central temperature decreases while the temperature at large radii ($r > 0.25r_{200}$) remains roughly the same. Our predicted temperature profiles are somewhat different from the observed ones (e.g., Vikhlinin et al. (2005)) which often show a similar behavior in the outer region but a decrease in the innermost region. The difference likely arises due to radiative cooling, which is not accounted for in our nonradiative simulations.

In the bottom panels of Figure 4, we plot the profiles of temperature defined as $kT/\mu m^2/\rho$, where $\mu$ is the number density of particles. These entropy profiles are consistent with previous results (e.g., Frenk et al. 1999; Ascasibar et al. 2003; Kay et al. 2004; Borgani et al. 2004; Voit et al. 2005). In particular, the entropy floor in the central region agrees well with that found by Ascasibar et al. (2003) who also performed their simulations with GADGET2 (see also Voit et al. 2005). In the outer region of halos, different SPH simulations yield consistent results. However, in the inner regions, we find that the higher the resolution, the lower the entropy floor. This can be understood as follows: at constant pressure, the entropy $s \propto T^{5/3}$; in the simulations with lower resolution the temperature is higher; as a result, the entropy will also be higher in low resolution simulations. Note results with the same SPH resolution but different DM resolutions (i.e., run A1 and A3) for the massive halo shown in the bottom left panel, but for the low-mass halo, the temperature and entropy in the very inner region in run A1 are somewhat higher than those in run A3.

Two-body heating is expected to be serious for poorly resolved halos with few particles: gas particles gain energy from collisions with DM particles and the gas distribution expands substantially. The trend of differences in the gas density profiles in low-mass halos for simulations with different resolutions is in agreement with this two-body heating effect. Steinmetz & White (1997) gave a rough estimate for when this effect is important (see their eqs. [5] and [6]). Even for the low-mass halos shown in Fig. 3, the total number of DM particles $N$ exceeds 9000 in A1 and 76,000 in A4. Taking $\ln \Lambda = 5$ in their equation (6), the two-body heating timescale is roughly $200/10^4$ times the crossing time at half-mass radius, which may be too long (see also the left panel in their Fig. 2, which shows negligible two-body heating for a galaxy-sized halo with 4000 particles). At least for the halos with mass larger than $10^{13} h^{-1} M_\odot$ in our simulations with highest mass resolution (run A4), two-body heating should be negligible.

4. ENERGY TRANSFER FROM DM TO GAS PARTICLES IN MERGERS

It is not entirely clear what causes the steepening in the DM profiles. One possibility is that during the assembly process, shocks produced during mergers between the progenitors can convert kinetic energy into thermal energy of gas particles. To conserve the total energy, DM particles lose some of their energy and sink further toward the center, which steepens the DM density profiles. As the merging histories of clusters in
cosmological simulations are complicated, they are not ideal for isolating the physical mechanism. Instead, we use non-radiative mergers between two spherically symmetric clusters with NFW density profiles to demonstrate the energy exchange between DM and gas particles.

We utilize the simulations of McCarthy et al. (2006). These simulations are gas-only and gas+DM simulations of head-on mergers with two equal-mass clusters using GADGET2. In the latter case, the gas traces DM initially and the ratio of gas to DM mass is set to $\Omega_b/\Omega_m \approx 16\%$. The virial mass of each cluster is $10^{15}M_\odot$ within $r_{200}$. In these simulations each cluster has 50,000 gas particles and 50,000 DM particles when present. The two clusters are initially well separated, with a distance much larger than $r_{200}$. The mergers start with the same infall velocity and separation in the gas-only and gas+DM simulations, so the initial masses and total energy are the same. The force-softening length is set to 10 kpc for both the gas and DM particles. More details, including the setup of initial conditions, can be found in McCarthy et al. (2006).

Figure 5 shows the resulting binned gas density profiles from the gas-only and gas + DM simulations after evolution for a Hubble time. Both the results of the gas-only and gas + DM simulations are similar outside $r \sim 150$ kpc. But inside this radius, the gas density is higher in the gas + dark matter simulation, implying that the dark matter must have transferred energy to the gas inside this radius. Figure 6 shows the evolution of the total energy of the DM from the gas + DM simulation. The energy has been normalized by its initial value. Note that the total energy is negative (the system is gravitationally bound), so if the ratio exceeds unity this implies that energy has been transferred to the gas. The figure clearly demonstrates that at the end of this simulation, approximately 7% of the DM’s total initial energy has been transferred to the gas. The same energy transfer procedure should have also occurred in the cosmological simulations.

5. SUMMARY AND DISCUSSION

In this paper, we performed a set of numerical simulations with nonradiative gas in the concordance cosmology, and compared the results with those of a pure DM simulation. The simulations have identical initial conditions but different force and mass resolutions. We carefully examined the effects of force resolutions and two-body heating. In summary, in simulations with hot gas, the DM distribution is more concentrated than those in DM-only simulation. The DM and total mass concentration parameters in the nonradiative gas simulations are on average about 10% and $\sim 3\%$ larger than those in the PDM simulation. We used idealized simulations of mergers of two clusters to demonstrate that the steepening of the DM profile is due to energy transfer from DM to gas particles (in shocks), which should also occur in our cosmological simulations.

The influence of baryons on the total mass distribution in our simulations is less significant than the results by Rasia et al. (2004) who reported a 10% increase in the concentration parameter for the total mass distribution. The difference is likely due to different SPH treatments used; in GADGET2 the entropy is conserved, while in GADGET1 it is not. New results obtained using GADGET2 by the same group are consistent with ours (A. Rasia 2006, private communication). Note also that we have many halos (about 400) while they had only 17 halos, so our statistics are better. Moreover, Ascasibar et al. (2003) also showed (their Fig. 1) that gas densities at the inner part of halos are higher in a conventional SPH code than those obtained in an entropy-conserving SPH code. Overall, the influence of hot gas on the mass distribution is quite weak in nonradiative gas simulations, especially for the total mass.

Observational measurement of this effect will be challenging. For example, the small change in the total mass concentration parameters will not have a substantial impact on the cross section of giant arcs.

The gas density profiles in our simulations show considerable scatter in their inner parts in different simulations, well beyond the softening length (see Fig. 3). We also show the results of temperature and entropy profiles to explain the effects of the resolution of SPH particles. While two-body heating of gas particles by DM particles is qualitatively consistent with the trend we see, quantitatively the timescale may be too long.

![Figure 2](image_url)

**Fig. 2.**—Mass dependence of the ratios of halo concentration parameters in runs A1 -A4 relative to those in the PDM run. The top and bottom panels are results for the DM and total mass, respectively. The symbols are the same as Fig.1. The solid horizontal lines indicate equality. The median values and lower and upper quartiles in each bin are indicated for five mass bins with equal numbers of galaxies. The median value and the range of mass in each bin are shown as horizontal error bars. The number of halos is 399, 400, 395, and 410, for the A1, A2, A3, and A4 runs, respectively.
for two-body heating to have substantial effects on the gas density profiles, in particular for the halos studied in run A4. Notice, however, that the uncertainty in gas profile has little effect on the DM and total mass distributions in our results as gas only contributes a small (but somewhat uncertain) fraction of the total mass.

The simulations presented above neglected important physical processes such as star formation, supernovae feedback, and heat conduction. For the group- and cluster-scale halos that we analyzed, the processes mentioned above are expected to be less important than in galaxies, nevertheless, their proper treatment is important in comparing data and theoretical predictions. Our study also ignores the differences in dynamical frictions between galaxies and DM halos. Because galaxies are located at the centers of DM halos, they can survive the tidal disruptions longer than the DM halos (e.g., Gao et al. 2004). As the dense cores of galaxies sink toward the centers, their kinetic energy can be transferred to and heat up the DM particles to make the DM distribution flatter (El-Zant et al. 2001, 2004). The uncertainties in the gas density profiles we found in the nonradiative case serves as a caution that while the incorporation of star formation and feedback processes is desirable, their physical treatment is likely to add another layer of uncertainty.

We acknowledge the anonymous referee for constructive comments which improved the paper. We thank Volker Springel for useful comments and suggestions on the draft as well as kindly providing the code GADGET2 before public release. W.P.L. thanks Kohji Yoshikawa and Mei Zhang for help on the simulations. This work is supported by grants from NSFC (10203004, 10125314, 10373012, and 10533030) and Shanghai Key Projects in Basic Research (04JC14079 and 05XD14019). S.M. and L.G. acknowledges support from CAS and Jodrell Bank. I.G.M. acknowledges support from an NSERC postdoctoral fellowship. The simulations were performed at the Shanghai Supercomputer Center.

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Fig. 3.— Density profiles for the most massive halo (top) and a group-sized halo (bottom) in our simulations. The filled dots indicate the density profile for the PDM run, while other lines indicate results for the total, DM and gas density profiles in runs A1, A3, and A4 (labeled inside the panels). The three dotted vertical lines indicate the softening length, $0.02r_{200}$ and $r_{200}$. The data points between the latter two are used in the profile fitting in A1, A3, and A4.
Fig. 4.— Temperature (top) and entropy profiles (bottom) for the two halos shown in Fig. 3. The line symbols are the same as in Fig. 3.
Fig. 5.— Gas density profiles in the gas-only (solid line) and in the gas + DM (dashed line) simulations of head-on collisions between two spherical NFW clusters (see §4 for more details).

Fig. 6.— Ratio of the total energy of the DM at time $t$ to the initial total energy in the gas + DM simulation. The dotted line indicates energy conservation. At $t \gtrsim 5$ Gyr, the dark matter has lost energy to the gas, as implied by a ratio larger than unity.