COLLISIONAL DARK MATTER AND THE STRUCTURE OF DARK HALOS

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ABSTRACT

We study how the internal structure of dark halos is affected if cold dark matter particles are assumed to have a large cross section for elastic collisions. We identify a cluster halo in a large cosmological N-body simulation and resimulate its formation with progressively increasing resolution. We compare the structure found in the two cases in which dark matter is treated as collisionless or as a fluid. For the collisionless case, the overall ellipticity of the cluster, the central density cusp, and the amount of surviving substructure are all similar to those found in earlier high-resolution simulations. Collisional dark matter results in a cluster that is more nearly spherical at all radii, has a steeper central density cusp, and has less—but still substantial—surviving substructure. As in the collisionless case, these results for a “fluid” cluster halo are expected to carry over approximately to smaller mass systems. The observed rotation curves of dwarf galaxies then argue that self-interacting dark matter can only be viable if intermediate cross sections produce structure that does not lie between the extremes we have simulated.

Subject headings: dark matter — galaxies: formation — methods: numerical

1. INTRODUCTION

Cold dark matter scenarios within the standard inflationary universe have proved remarkably successful in fitting a wide range of observations. While structure on large scales is well reproduced by the models, the situation is more controversial in the highly nonlinear regime. Navarro, Frenk & White (1995, 1996, 1997) claimed that the density profiles of near-equilibrium dark halos can be approximated by a “universal” form with singular behavior at small radii. Higher resolution studies have confirmed this result, finding even more concentrated dark halos than the original Navarro et al. (1997, hereafter NFW) work and showing, in addition, that cold dark matter (CDM) halos are predicted to have a very rich substructure with an order 10% of their mass contained in a host of small subhalos (Frenk et al. 1999; Moore et al. 1999a, 1999b; Ghigna et al. 1999; Klypin et al. 1999; Gottlober, Klypin, & Kravtsov 1999; White & Springel 2000). Except for a weak anticorrelation of concentration with mass, small- and large-mass halos are found to have similar structure. Many of these studies note that the predicted concentrations appear inconsistent with published data on the rotation curves of dwarf galaxies and that the amount of substructure exceeds that seen in the halo of the Milky Way (see also Moore 1994; Flores & Primack 1994; Kravtsov et al. 1998; Navarro 1998).

It is unclear whether these discrepancies reflect a fundamental problem with the CDM picture or are caused by the overly naive interpretation of the observations of the galaxy formation process (see Eke, Navarro, & Frenk 1998; Navarro & Steinmetz 1999; van den Bosch 1999). On the assumption that an explanation should be sought in fundamental physics, Spergel & Steinhardt (1999) have argued that a large cross section for elastic collisions between CDM particles may reconcile data and theory. They suggest a number of modifications of standard particle physics models that could give rise to such self-interacting dark matter, and they claim that cross sections that lead to a transition between collisional and collisionless behavior at radii of order 10–100 kpc in galaxy halos are preferred on astrophysical grounds. Ostriker (1999) argues that the massive black holes observed at the centers of many galactic spheroids may arise from the accretion of such collisional dark matter onto stellar mass seeds. Miralda-Escude (2000) argues that such dark matter will produce galaxy clusters that are rounder than observed and so can be excluded.

At early times the CDM distribution is indeed cold, so the evolution of structure is independent of the collision cross section of the CDM particles. At late times, however, a large cross section leads to a small mean free path and so to fluid behavior in collapsed regions. In this Letter, we explore how the structure of nonlinear objects (“dark halos”) is affected by this change. We simulate the formation of a massive halo from CDM initial conditions in two limits: purely collisionless dark matter and “fluid” dark matter. We do not try to simulate the more complex intermediate case in which the mean free path is large in the outer regions of halos but small in their cores. If this intermediate case (which is the one favored by Spergel & Steinhardt 1999 and by Ostriker 1999) produces nonlinear structure intermediate between the two extremes we do treat, then our results show that collisional CDM would give poorer fits to the rotation curves of dwarf galaxies than standard collisionless CDM. Further work is needed to see if this is indeed the case.

2. THE N-BODY/SMOOTHED PARTICLE HYDRODYNAMICS SIMULATION

Our simulations use the parallel tree code GADGET developed by Springel (1999; see also Springel, Yoshida, & White 2000). Our chosen halo is the second most massive cluster in the ΛCDM simulation of Kauffmann et al. (1999). We analyze
TABLE 1

| Run | $N_{\text{tot}}$ | $N_{\text{high}}$ | $m_p$ ($h^{-1} M_\odot$) | $l_s$ ($h^{-1} \text{kpc}$) |
|-----|-----------------|-----------------|----------------------|-----------------|
| S0  | $3.2 \times 10^6$ | $0.2 \times 10^6$ | $1.4 \times 10^{10}$ | 30               |
| S1  | $3.5 \times 10^6$ | $0.5 \times 10^6$ | $0.68 \times 10^{10}$ | 20               |
| S2  | $5.1 \times 10^6$ | $2.0 \times 10^6$ | $0.14 \times 10^{10}$ | 3.0              |

its structure in the original simulation and in two higher resolution resimulations. In the collisionless case, these are the lowest resolution members of a set of four resimulations carried out by V. Springel, G. Tormen, S. D. M. White, & G. Kauffmann (2000, in preparation) using similar techniques to those of NFW. Details may be found there and in Springel et al. (2000). These collisionless resimulations use GADGET as an $N$-body solver, whereas our collisional resimulations start from identical initial conditions but use the code’s smoothed particle hydrodynamics (SPH) capability to solve the fluid equations. The SPH method regards each simulation particle as a “cloud” of fluid with a certain kernel shape. These clouds interact with each other over a length scale that is determined by the local density and so varies both in space and time. The basic parameters of our simulations are tabulated in Table 1, where $N_{\text{tot}}$ is the total number of particles in the simulation, $N_{\text{high}}$ is the number of particles in the central high-resolution region, $m_p$ is the mass of each high-resolution particle, and $l_s$ stands for the gravitational softening length. Our cosmological model is flat with matter density $\Omega_m = 0.3$, cosmological constant $\Omega_{\Lambda} = 0.7$, and expansion rate $H_0 = 70$ km $^{-1}$ Mpc $^{-1}$. It has a CDM power spectrum normalized so that $\sigma_8 = 0.9$. The virial mass of the final cluster is $M_{200} = 7.4 \times 10^{14}$ $h^{-1} M_\odot$, determined as the mass within the radius $R_{200} = 1.46$ $h^{-1}$ Mpc, where the enclosed mean overdensity is 200 times the critical value.

3. RESULTS

On scales larger than the final cluster, the matter distribution in all our simulations looks similar. This is no surprise. The initial conditions in each pair of simulations are identical, so particle motions only begin to differ once pressure forces become important. Furthermore, the initial perturbation fields in simulations of differing resolution are identical on all scales resolved in both models, and even S0 resolves structure down to scales well below that of the cluster. As is seen clearly in Figure 1, a major difference between the collisional and collisionless models is that the final cluster is nearly spherical in the former case and quite elongated in the latter. The axial ratios determined from the inertia tensors of the matter at densities exceeding 100 times the critical value are 1.00 : 0.96 : 0.84 and 1.00 : 0.72 : 0.63, respectively. Again this is no surprise. A slowly rotating fluid body in hydrostatic equilibrium is required to be nearly spherical, but no such constraint applies in the collisionless case (see also Miralda-Escude 2000).

In Figure 2 we show circular velocity profiles for our simulations. These are defined as $V_\text{c}(r) = [GM(r)/r]^{1/2}$, where $M(r)$ is the mass within a sphere radius $r$; they are plotted at radii between $2l_s$ and $5R_{200}$. They agree reasonably well along each sequence of increasing resolution, showing that our results have converged numerically on these scales. Along the fluid sequence, the profiles resemble the collisionless case over the bulk of the cluster. In the core, however, there is a substantial and significant difference; the fluid cluster has a substantially

Fig. 1.—Projected mass distribution in our two highest resolution simulations. The collisionless case (S2) is on the top, and the fluid case (S2F) is on the bottom. The region shown is a cube of 15 $h^{-1}$ Mpc on a side.

Fig. 2.—Circular velocity profiles for our cluster simulations. These are plotted between the gravitational softening and $R_{200}$. The collisionless sequence is plotted using dashed lines, and the fluid sequence using solid lines.
steeper central cusp. The difference extends out to radii of about $0.5R_{200}$ and has the wrong sign to improve the fit of CDM halos to published rotation curves for dwarf and low surface brightness galaxies. (Note that in the fluid case we expect small halos to approximate scaled down but slightly more concentrated versions of cluster halos, as in the collisionless case studied by Moore et al. 1999a; this scaling will fail for intermediate cross sections because the ratio of the typical mean free path to the size of the halo will increase with halo mass.)

In Figure 3 we compare the level of substructure within $R_{200}$ in our various simulations. Subhalos are identified using the algorithm SUBFIND by Springel (1999), which defines them as maximal, simply connected, gravitationally self-bound sets of particles that are at higher local density than all surrounding cluster material. (Our SPH scheme defines a local density in the neighborhood of every particle.) Using this procedure, we find that 1.0%, 3.4%, and 6.7% of the mass within $R_{200}$ is included in subhalos in S0, S1, and S2 respectively. Along the fluid sequence the corresponding numbers are 3.0%, 6.4%, and 3.1%. The difference in the total amount results primarily from the chance inclusion or exclusion of infalling massive halos near the boundary at $R_{200}$. In Figure 3 we show the mass distributions of these subhalos. We plot each simulation to a mass limit of 40 particles, corresponding approximately to the smallest structures we expect to be adequately resolved in our SPH simulations. Along each resolution sequence the agreement is quite good, showing this limit to be conservative. For small subhalo masses there is clearly less substructure in the fluid case, but the difference is more modest than might have been anticipated.

4. SUMMARY AND DISCUSSION

An interesting question arising from our results is why our fluid clusters have more concentrated cores than their collisionless counterparts. The density profile of an equilibrium gas sphere can be thought of as being determined by its Lagrangian specific entropy profile, i.e., by the function $m(s)$ defined to be the mass of gas with specific entropy less than $s$. The larger the mass at low specific entropy, the more concentrated the resulting profile. Thus, our fluid clusters have more low-entropy gas than if their profiles were similar to those of the collisionless clusters. The entropy of the gas is produced by a variety of accretion and merger shocks during the build-up of the cluster, so the strong central concentration reflects a relatively large amount of weakly shocked gas. We study gas shocking in our models by carrying out one further simulation. We take the initial conditions of S1 and replace each particle by two superposed particles, a collisionless dark matter particle containing 95% of the original mass and a gas particle containing 5%. These two then move together until SPH pressure forces are strong enough to separate them. The situation is similar to the standard two-component model for galaxy clusters except that our chosen gas fraction is significantly smaller than observed values.

In this mixed simulation, the evolution of the collisionless matter (and its final density profile) is almost identical to that in the original S1. This is, of course, a consequence of the small gas fraction we have assumed. In agreement with the simulations in Frenk et al. (1999), we find that the gas density profile parallels that of the dark matter over most of the cluster but is significantly shallower in the inner $\sim 200$ h$^{-1}$ kpc. Comparing this new simulation (SIM) with its fluid counterpart (S1F), we find that in both cases the gas which ends up near the cluster center lay at the center of the most massive cluster progenitors at $z = 1$–3. In addition, it is distributed in a similar way among the progenitors in the two cases. In Figure 4 we...
compare the specific entropy profiles of the cluster gas. These
are scaled so that they would be identical if each gas particle
had the same shock history in the two simulations. Over most
of the cluster there is indeed a close correspondence, but near
the center the gas in the mixed simulation has higher entropy.
(This corresponds roughly to $r < 100 \, h^{-1} \, \text{kpc}$.) As Figure 4
shows, this is partly a numerical artifact; the two entropies
differ only at radii at which two-body heating of the gas by
the dark matter particles is predicted to be important in the
mixed case. (The effect is absent in the pure fluid simulation.)
The weaker shocking in the fluid case is evident from the
equivalent “entropy” profile of S1 in Figure 4. This lies between
those of the two fluid simulations and in particular significantly
above that of S1F in the central regions.

In conclusion, the effective heating of gas by shocks in the
fluid case is similar to but slightly weaker than that in the
mixed case. This is presumably a reflection of the fact that the
detailed morphology of the evolution also corresponds closely.
The difference in final density profile is a consequence of three
effects. In the mixed case the gas is in equilibrium within the
external potential generated by the dark matter, whereas in the
pure fluid case it must find a self-consistent equilibrium. In
addition, the core gas is heated by two-body effects in the mixed
case. Finally, in the pure fluid case the core gas experiences
weaker shocks.

Overall, our results show that in the large cross section limit,
collisional dark matter is not a promising candidate for im-
proving the agreement between the predicted structure of CDM
halos and published data on galaxies and galaxy clusters. The
increased concentration at halo center will worsen the apparent
conflict with dwarf galaxy rotation curves. Furthermore, clus-
ters are predicted to be nearly spherical and galaxy halos to
have similar mass in substructure to the collisionless case, al-
though with fewer low-mass subhalos. Intermediate cross sec-
tions would lead to collisional behavior in dense regions and
collisionless behavior in low-density regions with a consequent
breaking of the approximate scaling between high- and low-
mass halos. The resulting structure may not lie between the
two extremes we have simulated. Self-interacting dark matter
might then help resolve the problems with halo structure in
CDM models, if indeed these problems turn out to be real rather
than apparent.

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