WEAKLY SELF-INTERACTING DARK MATTER AND THE STRUCTURE OF DARK HALOS

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ABSTRACT

We study the formation of dark halos in a $\Lambda$CDM universe under the assumption that cold dark matter (CDM) particles have a finite cross section for elastic collisions. We compare evolution when CDM mean free paths are comparable to halo sizes with the collisionless and fluid limits. We show that a few collisions per particle per Hubble time at halo center can substantially affect the central density profile. Cross sections an order of magnitude larger produce sufficient relaxation for rich clusters to develop core radii in the range 100–200 $h^{-1}$ kpc. The structural evolution of halos is a competition between collisional relaxation caused by individual particle interactions and violent relaxation resulting from the infall and merging processes by which clusters grow. Although our simulations concentrate on systems of cluster size, we can scale our results to address the halo structure expected for dwarf galaxies. We find that collision cross sections sufficiently large to significantly modify the cores of such galaxies produce cluster cores that are too large and/or too round to be consistent with observation. Thus, the simplest model for self-interacting dark matter is unable to improve fits to published dwarf galaxy rotation curves without violating other observational constraints.

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

1. INTRODUCTION

Recent measurements of structure in the microwave background radiation (Lange et al. 2000; Hanany et al. 2000), although eliminating the "concordance" model (Bahcall et al. 1999), provide strong support for the general theoretical paradigm on which this model was based. Such cold dark matter (CDM) universes are in excellent agreement with observed large-scale structure, but may be inconsistent with the observed structure of nonlinear dark matter–dominated systems. Navarro, Frenk, & White (1997) claimed that the density profiles of virialized CDM halos are reasonably approximated by a "universal" form with singular behavior near its center. More recent simulations with higher resolution have confirmed this result, suggesting that the central cusps may be even steeper than the Navarro et al. (1997) profile (Moore et al. 1999b; Klypin et al. 1999; see also Jing & Suto 2000). Such structures appear inconsistent with published data on the rotation curves of dwarf galaxies (Moore 1994; Flores & Primack 1994), although this inconsistency may reflect limitations of the data rather than of the theory (van den Bosch et al. 2000; van den Bosch & Swaters 2000). There may also be a discrepancy between the rich substructure seen in simulations of CDM halos and the relatively small number of satellite galaxies observed in the Milky Way’s halo (Moore et al. 1999a; Klypin et al. 1999).

Spergel & Steinhardt (2000) suggested that a finite cross section for elastic collisions, such that the mean free path of CDM particles is short in halo cores but long in their outer parts, might alleviate these difficulties. Their proposal has attracted considerable attention. Ostriker (2000) argued that the massive black holes could grow naturally at the centers of galactic spheroids. Firmani et al. (2000) investigated how self-interacting dark matter might effect galaxy rotation curves. Hogan & Dalcanton (2000) considered how the structural properties of halos might scale with their mass. Burkert (2000) and Kochanek & White (2000) studied how collisional relaxation would affect the structure of isolated equilibrium halos, while Moore et al. (2000) and Yoshida et al. (2000) simulated cluster evolution in a cosmologically realistic context but in the fluid limit (very short mean free path). In this limit collisional dark matter produces more cuspy profiles than collisionless CDM and so gives even poorer fits to published rotation curves for dwarf galaxies.

In this Letter we continue exploring how collisions affect the structure of dark halos. We simulate the formation of a massive halo in a $\Lambda$CDM universe assuming scattering cross sections varying over a wide range. The inclusion of the infall and merging that occur when halos are embedded in their proper cosmological context leads to core evolution that is considerably more complex than the expansion followed by collapse seen in the simulations of Burkert (2000) and Kochanek & White (2000). Cross sections that would significantly modify the core structure of dwarf galaxies produce galaxy cluster cores that are inconsistent with observation.

2. THE SIMULATIONS

Our simulations use the parallel tree code GADGET developed by Springel (1999; see also Springel, Yoshida, & White 2000). We study the same cluster as Yoshida et al. (2000), who resimulated the second most massive object in the $\Lambda$CDM simulation of Kauffmann et al. (1999). In order to simulate elastic scattering of CDM particles, we adopt the Monte Carlo method introduced by Burkert (2000). We implement this scheme in the following manner. At each time step we evaluate the scattering probability for particle $i$,

$$P = \rho \sigma^* V_{rel} \Delta t,$$

where $\rho$ is the local density at the particle’s position, $\sigma^*$ is the scattering cross section per unit mass, $V_{rel} = |v_i - v_j|$ is the relative velocity between the particle and its nearest neighbor, and $\Delta t$ is the time step. This prescription is similar to Burkert’s...
but uses the relative velocity rather than the absolute velocity of particle $i$. Kochanek & White (2000) use a similar scheme but estimate the scattering rate more accurately by looping over a certain number of neighbors. However, the larger smoothing involved in such a procedure can itself introduce difficulties in regions with significant velocity gradients (Meiburg 1986), and so we prefer our simpler scheme, which should be unbiased even if somewhat noisier. We choose time steps small enough to ensure that a particle travels only a minor fraction of its mean free path within $\Delta t$. We assume each collision to be elastic, of hard-sphere type, and to have a cross section independent of velocity. Scattering is assumed isotropic in the center-of-mass frame, so that relative velocities are randomly reoriented in each collision. We carry out simulations for three values of $\sigma$ differing by factors of 10.

Most of our simulations employ $0.5 \times 10^6$ particles in the high-resolution region, with a mass per particle $m_p = 0.68 \times 10^9 h^{-1} M_\odot$. The gravitational softening length is set to $20 h^{-1}$ kpc, which is $\sim 1.4\%$ of the virial radius of the final cluster. We ran one simulation with 5 times better mass resolution and 7 times better spatial resolution to check for numerical convergence. All of our resimulations start from the same initial conditions. The background cosmology is flat with matter density $\Omega_m = 0.3$, cosmological constant $\Omega_k = 0.7$, and expansion rate $H_0 = 70$ km s$^{-1}$ 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

The large-scale matter distribution in all our simulations looks very similar. Because we start from identical initial conditions, the particle distributions differ only in regions where collisions are important. Figure 1 shows that the final cluster is more nearly spherical and has a larger core radius for a larger collision cross section. The quoted axial ratios are determined from the inertia tensors of the matter at densities exceeding 100 times the critical value. Miralda-Escudé (2000) argues that the ellipticity of cluster cores, as inferred from gravitational lensing observations, can be used to limit the interaction cross section. Among our final clusters, S1W-b and S1W-c are severely constrained by the limits he quotes.

In Figure 2 we show density profiles for all of our simulations. Also plotted in the bottom panel is the mean collision number per particle. (We counted collisions for each particle
throughout the simulation.) Figure 2 clearly shows the presence of a core whose extent depends on the cross section. For our intermediate cross section case (S1W-b), we also carried out a higher resolution simulation. The two density profiles agree very well (see Fig. 2), showing that our simulations have converged numerically on scales larger than the gravitational softening length. The mean collision count at cluster center is 3 for S1W-a, 8 for S1W-b, and 35 for S1W-c. Thus, only a few collisions per particle in a Hubble time suffice to affect the central density profile, and about 10 collisions per particle result in a core with $r_c \geq 100 \, h^{-1} \, \text{kpc}$. (We define the core radius as the point where the density profile becomes steeper than proportional to $r^{-1}$. Core radii by this definition are given on the right of Fig. 1.)

Unlike an isolated system, our cluster grows through successive mergers. Thus, the material in its central region is a mixture of the material from a number of its progenitors. Figure 3, a time sequence of density profiles for our S1W-c simulation, shows clearly how merger events interrupt the core evolution and produce low-density cores. We let this simulation run beyond the present time to $a = 1.72$, where $a$ is the expansion parameter normalized to its present value. During the time interval plotted, the cluster experiences major mergers at $a \sim 0.75$ and $a \sim 1.4$. Each of these events is associated with an increase of the core radius. Subsequent relaxation causes the core to shrink again and the central density to rise. For this relatively large cross section, relaxation-driven core expansion does not occur within the time interval shown. In contrast to this complex behavior, the virial mass of the cluster grows quite smoothly, approximately doubling between $a = 0.73$ and $a = 1.72$. Clearly, the core radius of the cluster at $a = 1$ results from an interplay between collisional relaxation driven by particle collisions and violent relaxation caused by mergers.

In Figure 4 we compare the amount of substructure within $R_{200}$ in our various simulations. We use the SUBFIND algorithm by Springel (1999) to identify subhalos in the final cluster. This identifies gravitationally self-bound sets of particles that are at a higher density than the smooth background of cluster material.

Local density is defined at each particle’s position in a smoothed particle hydrodynamics fashion. Using this procedure we find that 3.7%, 3.6%, 2.5%, and 0.7% of the cluster mass is included in subhalos in S1, S1W-a, S1W-b, and S1W-c, respectively. Although low-mass substructures are somewhat less abundant for larger cross sections, massive subhalos are not substantially disrupted in S1W-a and S1W-b. Many of the massive subhalos are $\sim 1 \, h^{-1} \, \text{Mpc}$ from the cluster center, where particle collisions are rare in these models (see the bottom panel of Fig. 2). Hence, “dark matter evaporation” (Spergel & Steinhardt 2000) is ineffective for them. On the other hand, the massive subhalos in S1W-c are totally disrupted. Infalling halos are rapidly stripped by collisions with “diffuse” cluster dark matter in this case.

4. SUMMARY AND DISCUSSION

Our simulations of cluster formation in a $\Lambda$CDM universe made of self-interacting dark matter show that collision rates exceeding 1 or 2 per particle per Hubble time at cluster center are sufficient to produce a constant-density core. Observations of strong lensing by clusters require their cores to be dense and small. Thus, to fit the cluster Cl 0024+1654, Tyson, Kochanski, & dell’Antonio (1998) needed a core radius of $35 \, h^{-1} \, \text{kpc}$ and a central surface density of $7900 \, h \, M_\odot \, \text{pc}^{-2}$. Recent Hubble Space Telescope observations of an unbiased sample of X-ray luminous clusters at $z \sim 0.2$ find thin giant arcs at similar radii ($10^\prime - 25^\prime$) in almost all of them (J.-P. Kneib 2000, private communication), showing Cl 0024+1654 to be quite typical. We find core radii of this order in our simulations for a cross section of 0.1 cm$^2$ g$^{-1}$ (see Fig. 1).

Predicted collision rates in dwarf galaxy cores are much smaller than in clusters for the core radii usually inferred from rotation curve data. Thus, for the archetypal example DDO154, Carignan & Beaulieu (1989) give as best-fit parameters a core radius $r_c = 3 \, \text{kpc}$ and a central surface density $\Sigma_0 = 141 \, M_\odot \, \text{pc}^{-2}$. (Note the lack of $h$ dependence because the distance is measured directly.) The central collision rate scales as $\Sigma_0^2 r_c^{-3}$, so collisions are inferred to be 60 times less frequent in DDO154 than in Cl 0024+1654 (for $h = 0.7$). Since particles in the cluster core have no more than a couple of collisions in a Hubble time (see Fig. 2), it is difficult to see how...
collisions could produce the large apparent core in DDO154. This agrees with the recent results of Dave et al. (2000), who concluded from their own simulations that cross sections of order 5 cm² g⁻¹ are needed to produce good agreement with the apparent cores of dwarf galaxies; they found at best marginal consistency for 0.5 cm² g⁻¹, a value that is still 5 times the upper limit we find to be consistent with cluster data.

A possible solution might seem to be a cross section about 2 orders of magnitude larger than in S1W-c. Dwarf galaxy halos would then look similar to a scaled version of S1W-c, with a core radius of about 4 h⁻¹ kpc for the parameters considered above, while rich clusters would be highly collisional and might have profiles approaching that in our “fluid” simulation. Our earlier work confirmed, however, that such clusters would be almost spherical; such large cross sections can thus be excluded following Miralda-Escudé’s (2000) argument.

A different resolution might be to introduce an interaction law that implies an energy-dependent cross section such that scattering is less effective in high-velocity encounters. This would reduce the difference between cluster and dwarf galaxy halos. This idea requires a more detailed physical model for the dark matter, and we do not pursue it further here. We note that \( \sigma \propto V^{-1} \) is required to make the collision rate at \( r \), approximately independent of halo mass. Another loophole might be for the cores of clusters to contain large amounts of baryonic dark matter, perhaps deposited by cooling flows. The cooling rates inferred from X-ray data appear too small for this to be viable (see, e.g., Peres et al. 1998).

In summary, our results suggest that collisional dark matter cannot produce core radii in dwarf galaxy halos as large as those inferred from rotation curve observations without simultaneously producing cluster cores that are too large and too round to be consistent with gravitational lensing data.

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REFERENCES

Bahcall, N. A., Ostriker, J. P., Perlmutter, S., & Steinhardt, P. J. 1999, Science, 284, 148
Burkert, A. 2000, ApJ, 534, L143
Carignan, C., & Beaulieu, S. 1989, ApJ, 347, 760
Dave, R., Spergel, D. N., Steinhardt, P. J., & Wandelt, B. D. 2000, preprint (astro-ph/0006218)
Firmani, C., D’Onghia, E., Avila-Reese, V., Chincarini, G., & Hernandez, X. 2000, MNRAS, 315, L29
Flores, R. A., & Primack, J. A. 1994, ApJ, 427, L1
Hanany, S., et al. 2000, preprint (astro-ph/0005123)
Hogan, C. J., & Dalcanton, J. J. 2000, preprint (astro-ph/0002330)
Jing, Y. P., & Suto, Y. 2000, ApJ, 529, L69
Kauffmann, G., Colberg, J. M., Diaferio, A., & White, S. D. M. 1999, MNRAS, 303, 188
Klypin, A. A., Gottlôber, S.,Kravtsov, A. V., & Khokhlov, A. M. 1999, ApJ, 516, 530
Kochanek, C. S., & White, M. 2000, preprint (astro-ph/0003483)
Lange, A. E., et al. 2000, preprint (astro-ph/00005004)
Meiburg, E. 1986, Phys. Fluids, 29, 10
Miralda-Escudé, J. 2000, preprint (astro-ph/0002050)
Mo, H. J., & Mao, S. 2000, MNRAS, in press (astro-ph/0002451)
Moore, B. 1994, Nature, 370, 629
Moore, B., Gelato, S., Jenkins, A., Pearce, F. R., & Quillen, V. 2000, ApJ, 535, L21
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999a, ApJ, 524, L19
Moore, B., Quinn, T., Governato, F., Stadel, J., & Lake, G. 1999b, MNRAS, 310, 1147
Navarro, J., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Ostriker, J. P. 2000, Phys. Rev. Lett., 84, 5258
Peres, C. B., Fabian, A. C., Edge, A. C., Allen, S. W., Johnstone, R. M., & White, D. A. 1998, MNRAS, 298, 416
Spergel, D. N., & Steinhardt, P. J. 2000, Phys. Rev. Lett., 84, 3760
Springel, V. 1999, Ph.D. thesis, Ludwig-Maximilian Univ., Munich
Springel, V., Yoshida, N., & White, S. D. M. 2000, NewA, submitted (astro-ph/0003162)
Tyson, J. A., Kochanski, G. P., & dell’Antonio, I. P. 1998, ApJ, 498, L107
van den Bosch, F. C., Robertson, B. E., Dalcanton, J. J., & de Blok, W. J. G. 2000, AJ, 119, 1579
van den Bosch, F. C., & Swaters, R. A. 2000, preprint (astro-ph/0006048)
Yoshida, N., Springel, V., White, S. D. M., & Tormen, G. 2000, ApJ, 535, L103