RevMexAA (Serie de Conferencias), **17**, 19–21 (2003)

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

THE STRUCTURE OF HALOS IN SELF-INTERACTING COLD DARK MATTER MODELS

P. Colín,[1] V. Avila-Reese,[2] O. Valenzuela,[3] and C. Firmani[4]

RESUMEN

Usando simulaciones de alta resolución, hemos estudiado la estructura y subestructura de halos correspondientes a galaxias tipo Vía Láctea y a cúmulos de galaxias para una cosmología ΛCDM con partículas oscuras autointeractuantes. La sección eficaz, σ_{DM}, en nuestros modelos puede ser constante o proporcional al inverso de la velocidad relativa, v_{12}. Esta última dependencia de σ_{DM} con v_{12} resuelve el problema del "núcleo empinado" de la cosmogonía ΛCDM y predice una población de subhalos similar a la que se observa en los halos CDM.

ABSTRACT

High-resolution numerical simulations were performed to study the structure and substructure of Milky Way- and cluster-sized halos in a ΛCDM cosmology with self-interacting (SI) dark particles, where the particle cross section, σ_{DM}, is assumed constant or inversely proportional to the relative velocity. We conclude that the cuspy halo problem at galaxy scales of the ΛCDM cosmogony can be solved in the latter case. At the same time, the subhalo population remains roughly similar to that seen on CDM halos.

Key Words: **COSMOLOGY: DARK MATTER — GALAXIES: HALOS**

1. INTRODUCTION

The potential problems of the popular ΛCDM model at small scales have motivated the search for modifications that keep the succesful predictions of the model at large scales unaltered. Two of these problems are that (a) ΛCDM halos seem to be more concentrated and cuspy than what is suggested by the rotation curves of dwarf and LSB galaxies (see references below), and that (b) the number of subhalos predicted by the ΛCDM model on galactic scales overwhelms the observed one (Klypin et al. 1999). While the latter problem has a well-motivated astrophysical solution (see e.g., Benson et al. in this volume), the former one seems to require a solution which goes beyond the standard model of structure formation. A posible solution for the "cuspy" problem was proposed by Spergel & Steinhard (2000) (see also Firmani et al. 2000) who introduced the concept of self-interacting (SI) DM particles within this context. The SIDM cross section per unit of particle mass, σ_{DM}, is a free parameter which may be constant or dependent on the relative velocity of the colliding particles, v_{12}: $\sigma_{DM} = \sigma_0 {v_{100}}^{-\alpha}$, where v_{100} is v_{12} in units of 100 kms^{-1}.

A number of authors have constrained the range of the pair (σ_0, α) of values and concluded that the relevant regime for structure formation is the optically thin one (small cross sections; see e.g., Hennawi & Ostriker 2002 and referenes therein). By means of cosmological simulations, we explore in more detail the effects of varying (σ_0, α) on halo structure and subhalo population (Colín et al. 2002, hereafter C2002). An outline of the results is presented in §3. In order to explore the viability of the SIDM model, it is important to establish the observational constraints. This is done in the next section.

2. OBSERVATIONAL CONSTRAINTS

Several recent observational studies, using the highest sensitivity and spatial resolution in HI, Hα and CO lines, show that halos of dwarf and LSB galaxies seem to be less concentrated in the center than what is predicted by the ΛCDM model (e.g., Côté, Carignan, & Freeman 2000; Blais-Ouellette, Amram, & Carignan 2001; Bolatto et al. 2002; Amram & Garrido 2002; de Blok et al. 2001a, 2001b; Marchesini et al. 2002; see also the contributions by Bosma and by de Blok in this volume). The inner slopes inferred for the halo density distribution are typically around −0.5, shallower than the slopes of ΛCDM halos. There are also pieces of evidence of soft cores in normal disk galaxies (e.g., Corsini et al. 1999; Firmani & Avila-Reese 2000; Borrielo & Salucci 2001; Salucci 2001) and in elliptical galaxies (Keeton 2001), although the evidence is less direct than in the case of dwarf and LSB galaxies.

An important question is that of the scaling laws of halo cores. Assuming the non-singular isothermal or pseudo-isothermal halo models, several authors have tried to find this law. For a sample of dwarf and

[1]Instituto de Astronomía, UNAM, Morelia, México.
[2]Instituto de Astronomía, UNAM, CU, México.
[3]Astronomy Department, New Mexico State University
[4]Osservatorio Astronomico di Brera, Merate, Italy

LSB galaxies with high-quality rotation curves and two clusters of galaxies studied with gravitational lensing, Firmani et al. (2000, 2001) have found that the halo central density, when plotted against the maximum circular velocity, v_{max}, exhibits a large scatter with no correlation with v_{max}; the core radius, on the other hand, tend to correlate with v_{max} with a slope smaller than 1. Other workers have arrived to similar conclusions (see references in C2002). The data on clusters have increased in the last two years, mainly from high-resolution Chandra X-ray studies. The mass distributions for most of the X-ray clusters are well fitted by both the NFW and the pseudo-isothermal profiles. The studies with strong gravitational lensing favour shallow halos.

For a sample of dwarf and LSB galaxies with high-resolution rotation curves and for X-ray and lensing clusters of galaxies, we infer that the central density $\rho_{c,-1}$, defined as the density where the logarithmic slope of the density profile becomes lower than -1, has values between $\sim 10^{16} - 10^{17}$ $h^2M_\odot Mpc^{-3}$ from dwarf- to cluster-sized halos, with no evidence of a dependence on v_{max}. The predictions of the ΛCDM model for $\rho_{c,-1}$ for cluster-sized halos are within this range, but for galaxy-sized halos, $\rho_{c,-1}$ is larger than 10^{17} $h^2M_\odot Mpc^{-3}$. Can the SIDM cosmology solve the discrepancy?

3. MODELS AND RESULTS

The Adaptive Refinement Tree (ART) N-body code (Kravtsov, Klypin, & Khokhlov 1997) has been used to run the N-body simulations. A pair of particles collide if the distance $d = -\lambda \ln(1 - P)$ ($\lambda = 1/\rho\sigma_{DM}$ is the mean free path and P is a random number distributed uniformly between 0 and 1) becomes lower than the distance $v_{12}\Delta t$, where v_{12} is the relative velocity between the particle and one of its nearest neighbors, and Δt is the time step. The ΛCDM model was used throghout.

The core evolutionary behavior of NFW halos with the self-interaction on is shown in our experiments with monolithic halos. Firstly, the core expands due to the heat inflow from the hotter surroundings (for CDM halos, the 3D velocity dispersion decreases towards the center). There is a radius below which quantities like the total energy or the heat capacity, C, become positive. Therefore, the heat inflow leads to the isothermalization of the core. Secondly, after the maximum expansion of the core, the region where $C > 0$ decreases, heat starts flowing from a zone where C is actually now negative. Thirdly, the gravothermal instability is triggered and the core collapses. The system moves from a minimum to a maximum entropy state. The time scales of these processes for monolithic halos depend on σ_{DM}. For cosmological halos these time scales can be modified by extra dynamical heating (e.g., mergers): the halo periphery can be heated and the temperature there can become higher than in the core, the heat flows to the core and it expands until the overall halo isothermalizes. This process can delay the core collapse, but will not reverse the gravothermal instability to a runaway core expansion.

We have further investigated Milky Way (MW)- and cluster-sized halos from cosmological simulations, using several values for the pair (σ_0, α). The parameter that defines the evolution under SI is the number of collisions per particle after a given time, $N_{col} \propto \rho\ \sigma_{DM}\ v_{rms}\ t$. From all of our runs, we see that if N_{col} at the present epoch is $\lesssim 2-5$, then the halo is either in the core-expansion phase or has just had the gravothermal catastrophe triggered. The halo density profiles are affected (flattened) only in the innermost regions, $r < 0.05R_{vir}$. When σ_{DM} is constant ($\alpha = 0$), the cores of low velocity halos are on average less influenced by SI than the high velocity ones; therefore, $\rho_{c,-1}$ will depend on scale (but see Davé et al. 2001). When $\sigma_{DM} \propto 1/v_{12}$ ($\alpha = 1$), we expect halos of different sizes to have roughly similar core densities (Firmani et al. 2001; Yoshida et al. 2001) Nevertheless, these simple reasonings apply strictly only for monolithic halos. The cosmological mass assembly history may dramatically influence the $z = 0$ structure of halos with a significant cross section; for example, for values of $\sigma_0 = 3$ cm^2gr^{-1} and $\alpha = 0$, we find that MW- or cluster-sized halos are or are not well inside the core collapse phase by $z = 0$; this depends essentially on whether halos have suffered recent major mergers. We see clearly that the smooth mass accretion is not important; only the violent mergers can delay the core collapse phase.

We find that only SIDM models with $\sigma_{DM} \propto 1/v_{12}$ are able to predict halo central densities that do not depend on scale, as observations suggest. For $\sigma_{DM} = 0.5 - 1.0(1/v_{100})cm^2gr^{-1}$, dwarf to cluster-sized halos have $\rho_{c,-1}$ values within the range inferred from observations. In Fig. 1, we present a comparison between a MW-sized SIDM ($\sigma_{DM} = 0.5(1/v_{100})cm^2gr^{-1}$) and a CDM halo (the so-called, MW-sized, fiducial halo in C2002). Slight differences can be noticed from this figure: (a) the core of the SIDM halo is less concentrated, the black spot at the center of the halo is less dark and appears uniformly spread over a larger area, (b) small subhalos are slightly more numerous in the SIDM halo and have a different radial distribution, and (c) the SIDM halo seems to be rounder (a quantitative and more

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

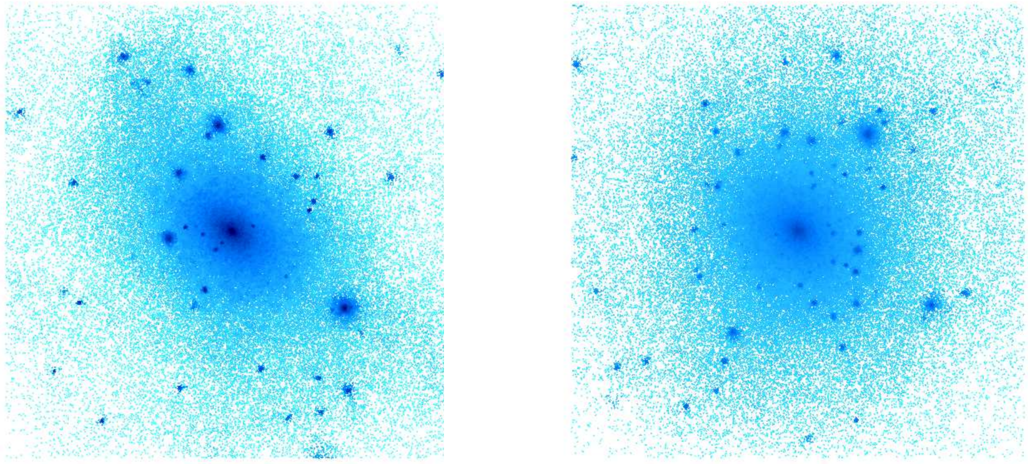

Fig. 1. Distribution of dark matter particles inside a box of 0.5 h^{-1}Mpc on a side centered on a MW-sized halo with $\sigma_{DM} = 0$ (left, CDM) and with $\sigma_{DM} = 0.5(1/v_{100})$ (right, SIDM). Particles are color-coded on a gray scale according to their local density. The local density at the particle positions was computed using SMOOTH. of Astronomy of the University of Washington.

detailed comparison can be found in C2002).

In general, we find that the number of subhalos within the SIDM halos simulated here is largely suppresed only for $(\sigma_0, \alpha) = (3.0, 0.0)$. Subhalos may survive a longer time in SIDM halos than in CDM ones because the inner tidal force in the former is weaker than in the latter. The structure and population of subhalos are determined by the interaction between the hot host halo particles and the cooler subhalo particles, rather than by internal processes in the subhalos. Overall, SIDM subhalos become puffier than their CDM counterparts; they are completely evaporated only in the limit of high σ_{DM}.

Our simulations also show that SI start flattening the inner density profiles of growing CDM halos since early epochs in such a way that the growth of super massive black holes by accretion of SIDM (Hennawi & Ostriker 2001) does not seem to be an efficient process, and therefore can not be used as a criterion to constrain SIDM models.

This work was supported by CONACyT grants 33776-E to V.A. and 36584-E to P.C.

REFERENCES

Amram, P., Garrido, O. 2002, in ASP Conf. Series 282 (astro-ph/0202475)
Blais-Ouellette, S., Amram, P., & Carignan, C. 2001, AJ, 121, 1952
Bolatto, A. D., Simon, J. D., Leroy, A., Blitz, L. 2002, ApJ, 565, 238
Borriello, A., Salucci, P. 2001, MNRAS, 323, 285
Colín, P., Avila-Reese, V., Valenzuela, O. & Firmani, C., ApJ, 581, 777 (C2002)
Côté, S. ., Carignan, C., & Freeman, K. C. 2000, AJ, 120, 3027
Corsini, E. M. et al. 1999, A&A, 342, 671
Davé, R., Spergel, D.N., Steinhardt, P.J., & Wandelt, B.J. 2001, ApJ, 547, 574
Firmani, C., D'Onghia, E., Avila-Reese, V., Chincarini, G., & Hernández, X. 2000, MNRAS, 315, L29
Firmani, C., D'Onghia, E., Chincarini, G., Hernández, X. & Avila-Reese, V. 2001, MNRAS, 321, 713
Hennawi, J.F., & Ostriker, J.P. 2002, ApJ, 572, 41
Keeton, C. R. 2001, ApJ, 561, 46
Klypin, A.A., Kravtsov, A.V., Bullock, J.S., & Primack, J.R. 2001, ApJ, 554, 903
Kravtsov, A.V., Klypin, A.A, & Khokhlov, A.M. 1997, ApJS 111, 73
Marchesini, D., et al 2002, ApJ, 575, 801
Salucci, P. 2001, MNRAS, 320, L1
Spergel, D.N. & Steinhardt, P.J. 2000, Phys. Rev. Lett., 84, 3760
Yoshida, N., Springel, V., & White, S.D.M. 2000, ApJ, 535, L103

P. Colín: Instituto de Astronomía, Universidad Nacional Autónoma de México, Campus Morelia, Apartado Postal 3–72, 58090 Morelia, Michoacán, México (p.colin@astrosmo.unam.mx).