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SHALLOW CORES IN THE DARK MATTER HALOS: SELF – INTERACTION IN ACTION?

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RESUMEN

Con base en datos observacionales para una muestra de galaxias dominadas por materia obscura y un par de cúmulos de galaxias, hemos encontrado que la densidad central del halo no depende de su masa y el radio del núcleo es proporcional a la velocidad de máxima de rotación. Estas leyes de escala están de acuerdo con halos CDM cuyas partes internas se expandieron por inestabilidades gravotérmicas si las partículas autointeractúan eficazmente sólo en estas partes. Encontramos que la sección de choque es inversamente proporcional a la dispersión de velocidades.

ABSTRACT

Using observational data for a sample of dark matter dominated galaxies and two clusters of galaxies, we have found that the central halo density does not depend on its mass, and the core radius is roughly proportional to the maximum rotation velocity. A good agreement with these scaling laws is obtained for CDM halos whose dense inner parts were expanded by gravothermal instabilities if the particles efficiently self–interact only in these parts. We find that the particle cross–section is inversely proportional to the velocity dispersion.

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

1. INTRODUCTION

During several decades, dynamical studies of galaxies, and groups and clusters of galaxies have pointed out to the existence of massive dark matter halos. On the other hand, according to current models of structure formation in the universe, luminous galaxies should form from the gas trapped within the deep gravitational wells of dark matter (DM) structures emerged from primordial density fluctuations. In these models, non–dissipative, cold, collisionless particles (cold dark matter, CDM) were required. The CDM structure formation scenario successfully accounted for a wide range of observations, in particular on large scales. However, on small scales, compared with observations this scenario seems to predict too much central concentration in the halos and too much substructure in Milky Way–size halos. These discrepancies have induced the introduction of some modifications to the CDM scenario, in particular, to the nature of the DM.

From the point of view of particle physics, a large list of candidate DM particles has been proposed but unfortunately, none of the particles that might constitute the universe's missing mass have been detected at present. Nevertheless, it is possible that astronomical observations may help us to constrict some of the properties of these particles. For example, as was mentioned above, the existence of soft cores in the dark halos appears to be not compatible with collisionless CDM particles. Therefore, astronomical studies about the halo properties – in particular of their cores – are crucial for understanding the nature of the dark particles and the structure formation in the universe, as was emphasized in a pioneering paper on this subject by J. Kormendy (1990; see also Kormendy 1988). Here, we summarize the halo core scaling relationships we have inferred from

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observations from dwarf galaxies through cluster of galaxies (Firmani et al. 2000a,b), and we dicuss some of the implications of our results on the nature of the DM particles and the formation of halos.

2. HALO CORE SCALING LAWS FROM OBSERVATIONS

Analysis of the original virialized *halo mass distribution* for most of the galaxies is uncertain due to the ambiguities in the estimate of the stellar mass–to–light ratios M/L and the gravitational pull the collapsing gas exerted over the inner parts of the halo. This is why we limited our study to only galaxies (i) strongly dominated by DM and (ii) with accurately measured rotation curves. The sample taken from the literature consists of six dwarf galaxies, nine LSB galaxies, and two late–type low luminosity galaxies (Firmani et al. 2000b). In all these cases, the galaxies are DM dominated. Even so, we have subtracted from the observed rotation curve the small disk contribution. The halo components were fitted to a non–singular isothemal model; thus, for each galaxy characterized by its maximum circular velocity $\mathrm{V_{max}}$ we estimate its central density ρ_c and core radius r_c. For the less DM dominated LSB and low–luminosity galaxies, we have roughly calculated the factor by which the halo component was "deformed" due to the disk pull over the DM using the adiabatic invariance approximation (see details in Firmani et al. 2000b). On galaxy cluster scales, we have used the surface mass distribution for the cluster CL0024+1654 derived from unprecedent high–resolution strong lensing mass maps (Tyson, Kochanski, & Dell'Antonio 1998), and for the cluster CL0016+16 derived from weak lensing studies (Smail et al. 1995). In both cases there is no evidence of a massive cD galaxy and the inner mass distribution is soft.

In Figure 1 we show the dependence of r_c on $\mathrm{V_{max}}$ we have found from the observational data. Although the scattering is large, within a large range in $\mathrm{V_{max}}$ we estimate that:

$$\rho_c(r) \approx 0.02\ \mathrm{M_\odot pc^{-3}} \qquad \text{and} \qquad r_c \approx 5.5 \left[\frac{V_{\max}}{100\mathrm{kms^{-1}}}\right]^{0.95} \mathrm{kpc}. \tag{1}$$

Similar results were found for a uniform sample of high and LSB galaxies of the Coma Ursa Major cluster (Verheijen 1997; §6). In this case, the rotation curve decompositions were made assuming M/L_K constant for all galaxies, and the halo component was fitted to a pseudo–isothermal model. In contrast, from a sample of Sc-Im and dwarf galaxies, Kormendy (1988; 1990) inferred that ρ_c decreases with the galaxy luminosity (or $\mathrm{V_{max}}$). Certainly, more efforts should be done in the future in order to increase the sample of objects and to reduce the uncertainties in the rotation curve decomposition techniques. We remark on the importance of strong gravitational lensing studies in order to directly probe the inner regions of the cluster of galaxies.

3. IMPLICATIONS OF THE INFERRED HALO CORE SCALING LAWS

The existence of soft halo cores and even more, the scaling laws obtained for DM dominated systems [eq.(1)], are in complete disagreement with the predictions of CDM models. Warm dark matter (WDM) has been proposed in order to solve the other conflict of the CDM scenario —the overlying number of guest (satellite) halos in a Milky Way–size halo. Cosmological N–body simulations have shown that the latter problem is indeed solved for a filtering scale in the power spectrum of ~ 0.1 Mpc which corresponds to a warm particle of ~ 1 KeV (Colín, Avila–Reese, & Valenzuela 2000). These authors have also shown that the density profiles of halos with masses much larger than that corresponding to the filtering scale ($\sim 10^9\ \mathrm{h^{-1}} M_\odot$) are very similar to those of the CDM models (see also Moore et al. 1999). Thus, even if the halos with masses near or smaller than the filtering mass would have a core, the more massive WDM halos will not obey the scaling laws inferred from observations in §2 (see also Avila–Reese, Firmani, & Hernández 1998).

Spergel & Steinhardt (2000) suggested other modifications to the nature of the DM particles: the introduction of self–interaction. In Firmani et al. 2000a, the *gravothermal expansion* was proposed as the mechanism able to produce soft cores in self–interacting CDM halos. The inner velocity dispersion profile of these halos increases with radius. Therefore, if particles are collisional, heat transfers inwards, the core expands and cools, exacerbating even more the temperature gradient. This process is similar to the postcollapse gravothermal oscillations in globular clusters (Bettwieser & Sugimoto 1984; Goodman 1987). For globular clusters, the core expansion halts when the inner dispersion velocity profile flattens; this occurs because there is also an outwards

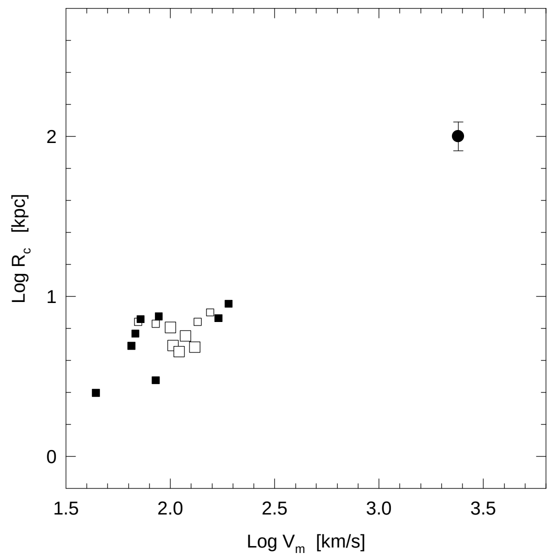

Fig. 1. The core radius R_c vs. $\mathrm{V_{max,100}}$ for dwarfs (filled squares), LSB galaxies (empty squares) and the CL0024+1654 cluster (filled circle).

heat flux from the maximum of the velocity profile. In the case of DM halos, we propose a collisional cross–section σ such that self–interaction is efficient only in the more dense halo regions. Besides, as the soft core grows, the core density decreases and at some point, self–interaction should become inefficient even in the inner regions. On the other hand, it is important to bear in mind that the CDM halo does not form instantaneously, but by a hierarchical mass aggregation process which establishes a cuspy inner structure with a positive velocity dispersion gradient.

Recent numerical simulations for a halo with a Hernquist density profile and with relatively small cross–sections per unit of the particle mass m_X ($\sigma_\star = \sigma/m_X$) have shown that the gravothermal processes acts in time scales that depend on the value of $\sigma_\star$ (Burkert 2000; Kochanek & White 2000; see also Quinlan 1996). An important constriction is that the halo lifetime should be in between the core expansion time and the core collapse time; otherwise either the shallow core will not have formed or will already be in its collapse phase. In Firmani et al. (2000a,b), using the average observed ρ_c and supposing that the collision time $t_{\rm col}$ in the core is close to the Hubble time, a lower limit for $\sigma_\star$ was estimated[5]: $\sigma_\star \approx 4\ 10^{-25} V_{\rm max,100}^{-1}$ cm^2/GeV, where $\mathrm{V_{max,100}}$ is $\mathrm{V_{max}}$ in units of 100 km/s. An important point to be noted is that $\sigma_\star$ depends on $\mathrm{V_{max}}$ or the maximum velocity dispersion, i.e. the cross–section is a function of the particle energy as in other classical physical interactions. For velocity dispersions corresponding to galaxy clusters, this value is close to the limit estimated by Miralda–Escudé (2000) from the observationally inferred ellipticity of the cluster MS2137–23.

One may think that the evolution of the collisionless DM halo occurs on dynamical time scales, $t_{\rm dyn}$, while those central regions of the halo affected by the gravothermal processes, evolve on relaxation time scales, $t_{\rm rel}$. The final halo density profile is the result of both dynamical processes. The simulations carried out by Burkert (2000) and Kochanek & White (2000, hereafter KW00) are for a halo that is already virialized. Therefore, these simulations do not describe the cosmological process of halo collapse and virialization. Kochanek & White find that the gravothermal core collapse occurs on time scales smaller than ~ 5 times the core formation time t_c independent of the value of $\sigma_\star$. On the other hand, $t_c \propto 1/\sigma_\star$. Thus, for $\sigma_\star$ small enough the halos may still be in their core expansion phase. Besides, if $\sigma_\star$ depends on $\mathrm{V_{max}}$ as we have inferred from observations, then larger halos should be today in earlier stages of gravothermal expansion than smaller halos, i.e. their central densities have not decreased too much. This, combined with the fact that in the hierarchical scenario smaller halos are intrinsically more concentrated than larger ones, could produce the invariance of ρ_c with the halo scale.

The simulations of KW00 are for a Hernquist (Hernquist 1990) halo, and they express $\sigma_\star$ in unities of r_H^2/M_h, where M_h is the halo mass and r_H is the scale radius of the Hernquist profile. Fitting the Hernquist profile to halos obtained in an N–body CDM simulation, one finds that r_H^2/M_h is roughly constant. In order

[5] Here we assume that $\mathrm{V_{max}} \approx v_{\rm rms,max}$; in fact, for CDM halos $\mathrm{V_{max}}$ is roughly 1.3-1.7 times larger than $v_{\rm rms,max}$.

to obtain more quantitative estimates, we have used results for a ΛCDM$_{0.3}$, h=0.7 model (Avila–Reese et al. 1999). We calculate r_H as $r_H = r_v/c_H$, where the virial radius r_v is defined as the radius where the average halo density is Δ_c times the background density (for our cosmology, $\Delta_c = 340$), and c_H is the concentration parameter which ultimately depends on the halo mass or V$_{\rm max}$ and is the only free parameter in the cosmological halo density profiles. From the results of the simulation, we find on the average c$_H = 37.5/($V$_{\rm max}$/km s$^{-1})^{0.36}$. The virial radius is proportional to V$_v$, the circular velocity at this radius, and for the Hernquist profile, V$_v = 2$V$_{\rm max}$c$_H^{1/2}/(1+c_H)$. We find that $r_H^2/M_h \approx 7\ 10^{-24}$ cm^2/GeV. Thus, in KW00 $\sigma_\star$ would be $\hat{\sigma}\times 7\ 10^{-24}$ cm^2/GeV. For $\hat{\sigma} = 1$, KW00 find that $t_c \sim 1.7$ dynamical times; after this the halo suffers the gravothermal core collapse. For a value of $\sigma_\star$ as that we have inferred from observations, for a V$_{\rm max} \approx 100$ km/s halo for example ($\sigma_\star \approx 4\ 10^{-25}$ cm^2/GeV), $\hat{\sigma} \sim 0.05$. The dynamical time (as defined in KW00) for a V$_{\rm max} \approx 100$ km/s halo is $\sim 5\ 10^8$ years. Therefore, the core formation time would be of the order of a Hubble time. Halos larger than V$_{\rm max} \approx 100$ km/s would have even larger core formation times.

4. CONCLUSIONS

• The halo core scaling laws inferred from observations of dwarf galaxies to galaxy clusters show that ρ_c does not depend on the halo mass or V$_{\rm max}$ and the core radius is roughly proportional to V$_{\rm max}$.

• If the dark particles are self–interacting with not very large cross sections, then gravothermal processes may produce a soft core in the DM halos. Using the observational data, we estimated the value of $\sigma_\star$ and found that is roughly proportional to V$_{\rm max}^{-1} \propto v_{\rm rms,max}^{-1}$.

• Results from numerical simulations of already virialized halos with self–interaction, show that if $\sigma_\star$ is of the order we inferred from observations, then t_c for small halos is close to the Hubble time, while for larger halos, t_c is probably even larger, i.e. these halos are still in early stages of gravothermal expansion. Numerical simulations and theoretical studies of collapsing and virializing DM halos where self–interacion is efficient only in the more dense inner regions are necessary in order to attain more quantitative conclusions.

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