Evidence of self-interacting cold dark matter from galactic to galaxy cluster scales

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ABSTRACT

Within the framework of the cold dark matter (CDM) cosmogony, a central cusp in the density profiles of virialized dark haloes is predicted. This prediction disagrees with the soft inner halo mass distribution inferred from observations of dwarf and low surface brightness galaxies, and some clusters of galaxies. By analysing data for some of these objects, we find that the halo central density is nearly independent of the mass from galactic to galaxy cluster scales with an average value of around $0.02 M_\odot/pc^3$.

We show that soft cores can be produced in the CDM haloes by introducing a lower cut-off in the power spectra of fluctuations and assuming high orbital thermal energies during halo formation. However, the scale invariance of the halo central density is not reproduced in these cases. The introduction of self-interaction in the CDM particles offers the most attractive alternative to the core problem. We propose gravothermal expansion as a possible mechanism to produce soft cores in the CDM haloes with self-interacting particles. A global thermodynamical equilibrium can explain the central density scale invariance. We find a minimum cross section capable of establishing isothermal cores in agreement with the observed shallow cores. If $\sigma$ is the cross section, $m_x$ is the mass of the dark matter particle and $v$ is the halo velocity dispersion, then $\sigma/m_x \approx 4 \times 10^{-25} (100 \ km/s/v) \ cm^2/GeV$.

Key words: galaxies: formation - galaxies: haloes - clusters: haloes - cosmology: theory - dark matter

1 INTRODUCTION

Constraining the nature of dark matter is presently one of the most relevant problems in cosmology and particle physics. The current most popular scenarios for structure formation in the universe are based on the inflationary CDM theory, according to which cosmic structures arise from small Gaussian density fluctuations composed mostly of non-relativistic collisionless particles. Luminous galaxies are thought to form by gas cooling and condensing into the dark matter haloes which grow by gravitational accretion and merging in a hierarchical fashion.

The question on the inner density profiles of the virialized dark matter haloes is at present controversial. In the last few years much observational and theoretical effort has been employed into investigating the inner structure of dark haloes. On galactic scales, the rotation curves of dwarf galaxies offer a way to study the inner mass distribution of their dark haloes directly since these galaxies are dominated by dark matter. By analysing the rotation curves of some near dwarf galaxies, Moore (1994), Flores & Primack (1994) and Burkert (1995) have shown that the central mass distribution of their dark haloes is soft, i.e. the haloes have a constant density core. A similar result concerns low surface brightness galaxies (LSB, hereafter) (de Blok & McGaugh 1997) even though the uncertainty in the observational data is larger than in the case of dwarf spirals. Hernández & Gilmore (1998) showed that the observed rotation curves of both LSB and normal large galaxies are consistent with a fixed initial halo shape, characterized by a significant soft core inner region. On scales of clusters of galaxies, unfortunately there is not much infor-
mation available. Recently, from strong gravitational lensing observations, Tyson, Kochanski, & Dell’Antonio (1998) have obtained an unprecedented high-resolution mass map for the cluster CL0024+1654, which has not a central cD galaxy, and found the existence of a soft core. Taken together these studies suggest the universality of constant density cores across both large mass scales and galactic types.

On the theoretical side, the structure of the CDM haloes was studied over a wide range of masses by means of high-resolution N-body cosmological simulations (e.g., Navarro, Frenk, & White 1997; NFW hereafter) and semi-analytical approaches (e.g., Avila-Reese, Firmani, & Hernández 1998). It was found that the universal density profile firstly introduced by NFW describes very well the mass distribution of most of the CDM haloes. This profile is univocally determined by the mass, and in the centre diverges as $\rho \propto r^{-1}$ producing a cusp in the core. Recent high-resolution N-body simulations have shown that, as the numerical resolution is increased, the inner profiles result even steeper than $r^{-1}$ (e.g., Moore et al. 1999b), making the CDM haloes more cuspy than in the case of the NFW profile.

So far, the predicted inner density profile of the CDM haloes seems to be in conflict with the observations. Another potential difficulty for the CDM models was recently reported: the N-body simulations predict an overly large number of haloes within group-like systems compared to observations (Klypin et al. 1999; Moore et al. 1999a). In light of these difficulties, the current stance of the hierarchical scenario of structure formation remains somewhat confusing because, in fact, this scenario successfully accounts for: the distribution of matter at large scales (Bahcall et al. 1999), the uniformity of the cosmic microwave radiation and its small temperature anisotropies, and the observationally inferred cosmological parameters.

The aim of this letter is to analyse the halo core properties inferred from observations which might suggest explanations of the origin as to the soft halo cores and clarify the discrepancies that appear on small scales with the hierarchical scenario of structure formation. We investigate whether some modifications on the initial conditions of this scenario are able to improve the results with respect to the observations. We demonstrate that the introduction of self-interaction in the CDM particles as was suggested by Spergel & Steinhardt (1999) offers the most viable solution to the core problem in a context that preserves the hierarchical CDM-based scenario.

2 HALO CENTRAL DENSITY FROM OBSERVATIONS

We select from the literature dwarf and LSB galaxies with accurately measured rotation curves and clearly dominated by dark matter. These restrictions considerably reduce ambiguities in the estimates of the dark matter mass distribution due to uncertain stellar mass-to-light ($M/L$) ratios and modifications of the original halo profile produced by the gravitational drag of baryons during disc formation. Hence the dark haloes of these galaxies can be rightly assumed almost “virgin”. These constraints reduce the sample to six dwarf galaxies: DDO154 (Carignan et al. 1998), DDO170 (Lake et al. 1990), DDO105 (Schramm 1992, quoted by Moore 1994), NGC3109 (Jobin et al. 1990), IC2574 (Martimbeau et al. 1994), NGC5585 (Côte et al. 1991). Six LSB galaxies are selected with the same criterion from a published sample: F568-v1, F571-8, F574-1: F583-1, F583-4, UGC5999 (de Blok & McGaugh 1997). The rotation curves measured for all these galaxies were used by the different authors to estimate the halo parameters, particularly the central density.

Our analysis also includes the density profile obtained for the cluster CL0024+1654 from a high resolution mass map derived using strong lensing techniques (Tyson et al. 1998). Because of the lack of a massive cD galaxy in the core, this cluster can be assumed to be dark matter dominated at the centre. Two clusters of galaxies, CL1455+22 and CL0016+16, with evident shallow mass profiles in the inner regions obtained by weak gravitational lensing studies (Smail et al. 1995) have also been considered, even though the uncertainty of the observational data is larger in these cases.

In Figure 1 we plot a very suggestive result: for a broad range of masses, the central density of the dark haloes is independent of mass (or circular velocity). Most dwarf galaxies (filled squares), LSB galaxies (open squares) and clusters (circles) indicate an average halo core density close to $\rho_c = 0.02 M_\odot/pc^3$. The arrow shows a fiducial value derived from a published sample of LSB galaxies (de Blok & McGaugh 1997). The galaxy error bars are based on the observational uncertainty, and when possible from the range given by the maximum and minimum disc models. The cluster error bars take into account the uncertainty in observations and in a normalization factor of three in going from strong to weak lensing techniques (Wu et al. 1998).

This observational evidence makes the cosmological puzzle quite complex: how can one explain the origin of soft halo cores with roughly the same central density over the entire mass range sampled?

3 SHALLOW CORES FROM COLLISIONLESS COLD DARK MATTER

As was discussed above, observations seem to show that the inner density profile of the dark matter haloes is (i) shallow, and (ii) with a central value independent from the total halo mass (or maximum circular velocity $V_m$). These facts disagree with the predictions of the hierarchical CDM models. Now, we investigate some alternatives which might alleviate these difficulties within the cosmological context. For this we have performed a quantitative study of the CDM halo profiles using a semi-numerical method (Avila-Reese, Firmani, & Hernández 1998) aimed at calculating the collapse and virialization of spherically symmetric density fluctuations starting from an arbitrary mass aggregation history. Results obtained with this method are in excellent agreement with those of the N-body simulations (see Avila-Reese et al. 1999; Firmani & Avila-Reese 2000). The method is based on a generalization of the secondary infall model where non-radial motions and adiabatic invariance are taken into account. The only free parameter is the orbital parameter of particles (the perihelion to aphelion ratio) which regulates the thermal orbital energy of the system. This parameter is fixed independently of the halo mass and is constant during
halo formation. Cosmological N-body simulations suggest \( r_{\text{peri}}/r_{\text{apo}} \approx 0.2 – 0.3 \) (see Ghigna et al. 1998).

Recently, Moore et al. (1999b) have simulated CDM haloes formed by monolithic collapse with N-body simulations introducing for this a lower cut-off at some wavelength in the power spectrum of fluctuations which suppresses substructures. The result was that the steep inner density profile of the haloes persisted. We suggest that this result might be partially a consequence of the lack of thermal orbital energy. In a monolithic collapse scenario the thermal orbital energy plays a significant role in producing soft cores: as \( r_{\text{peri}}/r_{\text{apo}} \) increases a larger soft core is obtained. The density profiles of our haloes obtained for a CDM model with a lower cut-off in the variance of the power spectrum and a non zero initial thermal content, present soft cores. However, these models are unable to predict the observed central density trend shown in Figure 1 (Avila-Reese et al. 1998). In fact, the central density \( \rho_c \) increases with \( V_m \) in such a way that if \( \rho_c \) is reproduced at galactic scales, for the cluster scales, \( \rho_c \) overshoots the observed value by more than an order of magnitude. A hypothetical injection of thermal energy to the dark matter at a specific time in the life of the universe leads to a similar negative result.

An interesting way to produce soft halo cores in agreement with observations is to simply truncate the hierarchical halo mass aggregation histories at a given redshift towards the past. This may be done assuming that the halo mass fraction instantaneously collapses with some thermal energy (monolithic thermal collapse), while the rest of the mass is aggregated at the normal hierarchical rate. We have calculated the density profiles for haloes whose mass aggregation histories correspond to a hierarchical flat ΛCDM model (\( \Omega_m = 0.3, h=0.7, \sigma_8 = 1 \)) from \( z = 5 \) and \( r_{\text{peri}}/r_{\text{apo}} = 0.3 \); before this epoch the hierarchical aggregation was truncated. The results for this toy model are in good agreement with the observations: the haloes have a soft core, the core densities are independent from the mass and have a value similar to that what observational inferences indicate. It is interesting to note that the most distant OSOs and galaxies are at redshifts \( z \approx 5 \). Although the toy model presented here might look attractive, it is difficult to imagine a physical process capable of delaying the collapse of the central parts of the CDM haloes until \( z \approx 5 \).

### 4 SHALLOW CORES FROM SELF-INTERACTING COLD DARK MATTER

Self-interacting dark matter has been proposed as a possible solution for two potential conflicts of the hierarchical CDM models (Spergel & Steinhardt 1999; Hannestad 1999): the shallow core of the haloes and the dearth of dwarf galaxies in the Local Group. Astrophysical consequences of collisional dark matter have been pointed out by Ostriker (1999). It is easy to show that a configuration with the NFW density distribution is very far from thermal equilibrium: the inner velocity dispersion (temperature) has a positive gradient. Consequently, the presence of some self-interaction in the CDM particles introduces in the dark haloes a process of thermalization with heat transfer inwards, avoiding the formation of a cuspy profile. Heat capacity in the core is negative. This is a typical property of self-gravitating systems, like the interiors of the stars. For this reason, the heat transfer inwards cools the core exacerbating even more the temperature gradient. The heat transfer inwards increases causing the core to expand and cool due to gravothermal instability, leading to runaway core expansion. This physical mechanism is the key point for core expansion if self-interaction is effective. This process is similar to the post-collapse gravothermal instability well-known in dynamical studies of globular clusters (Bettwieser & Sugimoto 1983) where the minimum central density is reached roughly after a thermalization time.

The expansion of the core does not last forever. Since as the core expands the central density decreases, this would make the self-interaction less efficient and the core formation mechanism a self-limiting process. Although attractive, this mechanism is difficult to investigate because of our lack of knowledge regarding the cross section of the self-interacting dark matter particles. For this reason we start our analysis with a thermodynamical approach: we shall estimate the central density of CDM haloes assuming a thermodynamical equilibrium is reached due to strong self-interaction of the CDM particles. The final result will be the formation in the CDM halo of a central isothermal non-singular density profile established by competition between 1) mass and energy hierarchical aggregation, and 2) the thermalization due to self-interaction. The hierarchical mass and energy aggregation process tends to establish a NFW density profile (with the corresponding heat transfer inwards) while the self-interaction process tends to lead the system to a thermal equilibrium with the corresponding formation of a shallow core. For a given mass, the halo formed by a hierarchical mass aggregation identifies a gravitational binding energy (or \( V_m \)). Using this mass and binding energy to rescale a thermodynamical equilibrium configuration it is easy to find:

\[
\rho_c = \alpha \frac{V_m^6}{M^2} \frac{M_\odot}{pc^3}
\]

where \( V_m \) is in km/s, \( M \) is the halo mass in \( M_\odot \) and \( \alpha \) is a constant given by the detailed shape of the final equilibrium configuration. Since for the CDM haloes a tight relationship between their mass and circular velocity of the kind \( M \propto V_m^n \) with \( n \approx 3.2 \) is predicted (Avila-Reese et al. 1998,1999), eq. (1) implies that \( \rho_c \) is roughly invariant with respect to the mass or \( V_m \) as observations point out (Fig. 1). This strongly suggests that indeed a thermalization process due to dark matter self-interaction is acting in the CDM haloes.

Unfortunately, there is not a single final thermal equilibrium configuration, and as Lynden-Bell & Wood (1968) pointed out, some of configurations are even unstable. The King and Wooley configurations are examples of systems that have reached thermal equilibrium. They are characterized by a form parameter that may be related to the entropy of the system. A fiducial value for the central density of the CDM haloes with self-interaction may be estimated using a King or a Wooley profile at the state of maximum entropy (Lynden-Bell & Wood 1968). For these cases we derive respectively \( \alpha = 1.3 \times 10^9 \) (short-dashed line in Fig. 1) and \( \alpha = 2.6 \times 10^9 \) (long-dashed line in Fig. 1) in the appropriate units. The case of maximum entropy for a King profile corresponds to a value of the form parameter of 8.5. A lower limit
for the density may be roughly estimated from the dynamical evolution of globular clusters based on the Fokker-Planck approximation (Spitzer & Thuan 1972), starting from a uniform spherical distribution (this initial condition will lead to a central density lower than the density reached by the thermalization of a steep initial profile). The rescaling for this model taken at the first thermal equilibrium state gives us $\alpha = 1.7 \times 10^9$ (dotted curve in Fig.1).

Global thermal equilibrium is reached when the self-interaction cross section is sufficiently large in order for the profile. From the observational data it is possible now to infer an estimate of the self-interaction cross section. If $n$ is the dark particle number density, $\sigma$ the cross section and $v$ the dispersion velocity, assuming the collision time in the core $\tau = 1/(n \sigma v)$ close to the Hubble time we obtain:

$$\frac{\sigma}{m_x} \approx 4 \times 10^{-25} \left( \frac{0.02 \, M_{\odot} \, pc^{-3}}{\rho_c} \right) \left( \frac{100 \, km \, s^{-1}}{v} \right) \, cm^2 / GeV(2)$$

with $m_x$ the mass of the dark matter particle and $\rho_c$ the central density. It is interesting to point out that for velocity dispersions corresponding to galaxy clusters this value is close to the upper limit estimated by Miralda-Escudé (2000) from the observationally inferred ellipticity of the cluster MS21137-23.

5 SUMMARY

The discovery of a soft core in the cluster of galaxies CL0024+1254 by strong gravitational lensing measurements and the rotation curves of dark-matter dominated dwarf and LSB galaxies indicate that dark matter haloes have shallow inner density profiles from galactic to cluster scales. Studying in detail the observational data available for these cosmic objects, we found that the halo central density is nearly invariant with respect to the mass from galactic to cluster sizes.

We investigated different mechanisms and models for halo core formation within the hierarchical CDM scenario. We have shown that a lower cut-off at some wavelength in the CDM power spectrum and the assumption of high particle orbital thermal energies produce soft cores in the haloes, but the invariance of $\rho_c$ with respect to the mass is not reproduced. A more viable solution to the core problem is the introduction of self-interaction in the CDM particles. Being this the case, we proposed the gravothermal expansion as the mechanism responsible for the formation of soft cores in a hierarchical CDM scenario.

Using a thermodynamical approach we have estimated the central density of haloes in the case of maximum efficiency for self-interaction and found good agreement with the values inferred from observations. The central density in this case scales with the halo mass and its maximum circular velocity as $\rho_c \propto V_m^3 / M^2$. This result implies that $\rho_c$ is roughly constant because for the CDM haloes $M \propto V_m^n$ with $n \approx 3.2$. If thermal equilibrium is restricted to the core, then the cross section given by eq.(2) may be derived consistently with observations. The cases analysed here, corresponding to a global and a local thermal equilibrium respectively, represent two limiting cases between which dark matter self-interaction may generate isothermal cores compatible with observations. We exclude from our analysis the extreme case of a very strong self-interaction which may lead the core to a gravothermal catastrophe with a central density profile steeper than NFW. Such extreme assumption of large cross section may be immediately ruled out because a singular isothermal core will be produced in contradiction with observations.

We stress the relevance confirming the existence of soft cores with scale invariant densities would have. In particular, the construction of high-resolution mass maps with gravitational lensing techniques for the inner regions of clusters is of great interest.

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Figure 1. Halo central density vs. maximum rotation velocity for dwarf galaxies (filled squares), LSB galaxies (open squares) and galaxy clusters (filled circles). The plot shows a region predicted by gravothermal models where a thermodynamical equilibrium is reached. The upper limit of the region (state of maximum entropy) is estimated for a Wooley (long-dashed line) and a King (short-dashed line) density profile. A dynamical model starting from a homogeneous sphere provides an estimate of the lower limit for the halo central density (dotted curve).