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DARK BARYONS AND THE PROFILE CRISIS IN COLD DARK MATTER HALOS

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ABSTRACT

This Letter proposes that the "profile crisis" in cold dark matter halo models is partly due to a weakly dissipative dark baryonic component. This component is built by rescaling the rotation curves of faint galaxies onto those of bright systems, and we argue that the collapse factor of the baryonic disk relative to the halo must be a constant. If this component is made of molecular gas in a frozen form, a large hole is expected in the central region that is due to UV heating by the stellar component. This hole, combined with a weakly peaked distribution of halo particles, may mimic an isothermal halo core that is wrongly attributed to the particles alone. Halos made of cold particles with or without a finite-scattering cross section are considered in this context. For faint objects, a concordance model is achieved with roughly half the mass in baryons, a mass concentration $c_M \approx 6.2 \pm 0.5$, and a inner profile $\rho \propto r^{-0.5 \pm 0.3}$ at $r = 0$ for the halos.

Subject headings: dark matter — galaxies: kinematics and dynamics

1. INTRODUCTION

The maximum-amplitude fluctuations on the cosmic microwave background imply that the observed structures in the universe cannot be built from perturbations in the hot baryonic plasma only without the help of gravitational instabilities born earlier in a gas of nonbaryonic particles. Such particles cannot be mainly relativistic because of the damping of fluctuations by free streaming in that case (Kolb & Turner 1990). Most cosmological models studied today are variants of a scenario in which perturbations start in a medium of massive weakly interacting particles (WIMPs), namely, the cold dark matter (CDM) scenario (Peebles 1982). Theoretical physics provides an excellent WIMP candidate that is already nonrelativistic at decoupling, the neutralino (Jungman, Kamionkowski, & Griest 1996); however, the halos derived from the CDM paradigm do not fit all the rotation curves (Navarro & Steinmetz 2000; Sellwood 2000). Halo simulations indicate that CDM profiles suffer two main drawbacks: they have overly dense cores (Moore 1994; Flores & Primack 1994) and singular profiles, which are not seen in the dark halos of dwarf spiral galaxies (e.g., de Blok et al. 2001).

Several theories designed to modify the shape of CDM halos and motivated by particle physics have been recently proposed: particles may be self-interacting (Spergel & Steinhardt 2000), warm (Colín, Avila-Reese, & Valenzuela 2000), fluid (Peebles 2000), or annihilating (Kaplinghat, Knox, & Turner 2000). In the context of interstellar matter, Pfenniger & Combes (1994) and Irwin, Widraw, & English (2000) explored the possibility that dark matter might be made of dark gas distributed in a fractal hierarchy, like other observed molecules. The fact that the halos shrink with the luminosities of the parent galaxies, i.e., the observed baryons have a higher collapse factor in dwarf galaxies than in bright systems, leads to the proposal of a dark disk component surrounding the stellar and gaseous disk, in addition to the nondissipative halo (Giraud 2000a, 2000b, 2000c). This Letter uses this hypothetical baryonic weakly dissipative dark gas as an alternative to alleviate the "profile crisis" in CDM models. Self-interacting dark matter (SIDM) models, which have hadron-like cross sections, are also considered since they provide upper limit profiles for WIMP-like particles; i.e., together with the CDM models, they bracket the profiles of particles with nonzero cross sections.

2. THE HYPOTHESIS OF DARK BARYONS AND COUPLED HALOS

2.1. *The Hypothesis of Dark Baryons*

The data in this Letter are the universal rotation curves of Persic, Salucci, & Stel (1996), to which more recent data, taken from the literature, have been added. These curves are an average of hundreds of observed rotation curves, normalized to their optical radii $r_{\rm opt}$ and binned by luminosity from the faintest disk galaxies $\langle M_I \rangle = -18.4$ to the brightest spiral galaxies $\langle M_I \rangle = -23.1$, in 10 bins. The radial extent of each average curve is $2r_{\rm opt}$. Let us consider a bright and a faint rotation curve. In Figure 1, the universal curve of galaxies with an average magnitude $\langle M_I \rangle = -18.4$ has been rescaled in radius, adjusted in velocity, and plotted over the universal rotation curve of objects with $\langle M_I \rangle = -21.2$. This figure shows that there is a solution such that the faint curve matches the inner part of the bright curve out to $\approx 1 r/r_{{\rm opt}(\langle M_I \rangle = -21.2)}$. This geometrical construction may be done for all the galaxy bins, starting from $\langle M_I \rangle = -23.1$, with a scale factor decreasing with decreasing luminosity. This is as if the rotation curves of faint systems are sampling the inner part of similar rotation curves of brighter objects.

If protogalaxy systems have acquired their angular momentum by tidal torques from their neighbors, because all systems experienced statistically the same external torques, the dimensionless spin parameter j is a constant (see, e.g., Efstathiou & Silk 1988). Therefore, the collapse factor, i.e., the ratio of the radius of the disk to the halo, which is inversely proportional to j, is statistically a constant. In this context, the two rotation curves shown in Figure 1 must be described with approximately the same disk and halo components. Because the intrinsic stellar disk extent of a $\langle M_I \rangle = -18.4$ galaxy, measured in optical radius units, is about half that of a $\langle M_I \rangle = -21.2$ galaxy, this condition implies the existence of a supplementary component that complements the visible disk in faint systems. Because H I gas is not sufficient for filling this component entirely, a dark baryonic component has been proposed (Giraud 2000a, hereafter G00a). The process of star formation requires a critical

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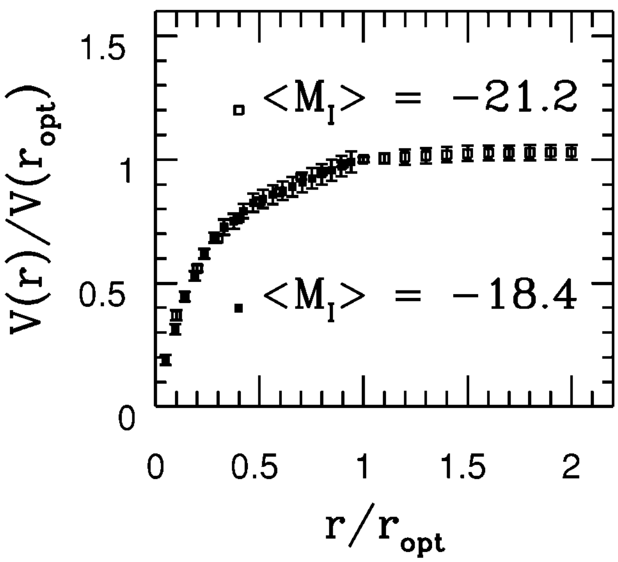

FIG. 1.—Universal rotation curve of $\langle M_I \rangle = -21.2$ spiral galaxies (*open squares*) plotted as a function of optical radius $r_{\rm opt}$ and normalized to its rotation velocity at $r_{\rm opt}$ and that of $\langle M_I \rangle = -18.4$ galaxies rescaled by a factor 0.47 in $r_{\rm opt}$ and adjusted in velocity to match the $\langle M_I \rangle = -21.2$ curve.

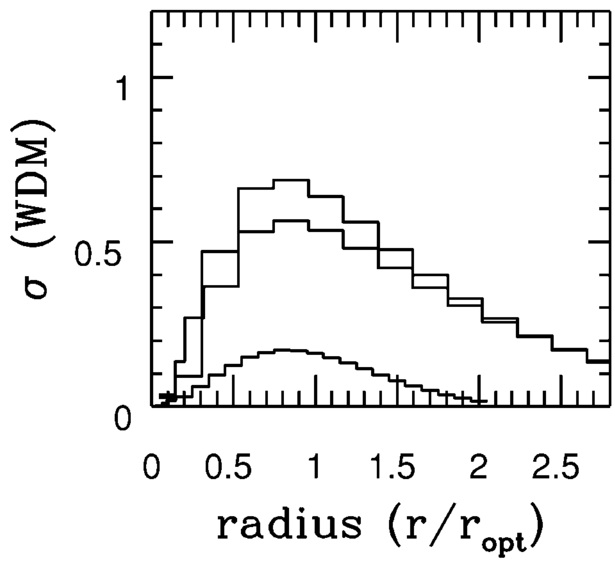

FIG. 2.—Normalized surface density distribution of the weakly dissipative dark matter (WDM) component for mass models of $\langle M_I \rangle = -18.4$ (*upper histogram*), $\langle M_I \rangle = -19.4$, and $\langle M_I \rangle = -21.2$ (*lower histogram*) universal galaxies.

surface density; therefore, one may understand that dwarf disks are intrinsically smaller because the critical density is reached at a smaller radius.

2.2. *The Hypothesis of Coupled Halos*

Let us consider the brightest galaxies, namely, those with $\langle M_I \rangle = -23.1$. Our objective is to build a disk-halo model for these objects; this models will be replicated in fainter systems by adding dark baryons to the observed distributions. In such bright systems, the gas fraction at $r < 1.5 r_{\rm opt}$ is negligible, and we assume throughout this Letter that, for these objects, the baryonic dark fraction is also negligible. We know that there is a degeneracy in disk-halo decompositions even in the simplest model made of an exponential disk and a halo. To overcome this degeneracy, we consider the empirical Tully-Fisher (1977) relation. This relation, between the stellar luminosity of a disk galaxy and the disk + halo maximum rotation velocity, requires a hidden relation between the disk and halo parameters. A form of such a missing term was derived by Zwaan et al. (1995). The relation of coupling between disk and halo mass distributions was introduced in Giraud (1998):

$$M_d(r) = \gamma M^{1/2}(r) r, \tag{1}$$

where M is the disk mass and M_d is the halo dark mass; this is the simplest relation that allows one to recover Zwaan's relation and to derive the Tully-Fisher relation from the virial theorem (eqs. [17] and [18] in G00a). In such models, the constant γ characterizes the relative importance of the dark halo with respect to the luminous mass, independently of radius, and is proportional to the dimensionless spin parameter j (see Appendix in Giraud 1998). The dispersion in the Tully-Fisher relation results from the dispersion in γ, namely, in j. The exponent measured in the Tully-Fisher relation depends on the systematics of the total disk (stars, gas, and any dark baryons) mass-to-luminosity ratio.

The disk-halo model for $\langle M_I \rangle = -23.1$ systems is the best fit shown in Figure 13 of G00a. Generically, a halo coupled with an exponential disk has an inner profile in $\rho \propto r^{-1}$, and its rotation curve is flat at $r > r_{\rm opt}$. Coupled halos are degenerated; i.e., their rotation velocities are indefinitely flat at large radii.

3. THE MODELS

3.1. *The Dark Disks*

There is a large amount of freedom in the possible models. The gas + dark baryonic component is mainly the difference between the disks in bright systems and those in faint systems after rescaling the rotation curves. This difference creates a central hole that is due to the small disk. Thus, in order to make simple models, we consider a surface density distribution with a central hole and the same radial position of the maximum for the gas + dark baryons. This is illustrated in Figure 2. The coupled halos are deduced by adjusting the stellar mass-to-light ratio, the maximum value of the gas + dark disk distribution, and allowing small corrections in γ. The models obtained for the two faintest bins, $\langle M_I \rangle = -18.4$ and $\langle M_I \rangle = -19.5$, are shown in Figure 3. They differ from the best-fit models in Figure 13 of G00a because here the dark baryonic distribution

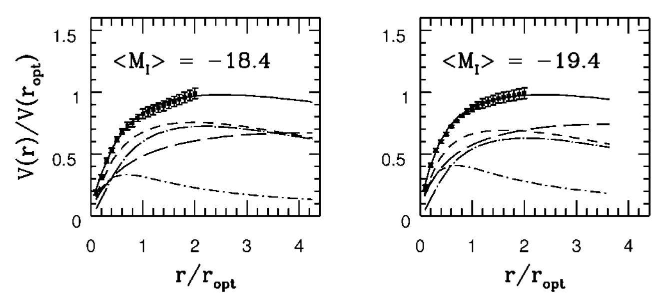

FIG. 3.—Coupled halo mass models vs. the average rotation curves for galaxies with magnitudes $\langle M_I \rangle = -18.4$ (*left*) and $\langle M_I \rangle = -19.4$ (*right*). The short dashed line is the total baryonic component that includes the stellar exponential disk (*dot–short-dashed line*) and the gas + dark gaseous component (*dot–long-dashed line*). The long dashed line is the halo coupled with the baryonic component. The solid line is the model fitted (baryons + halo) to the rotation curve.

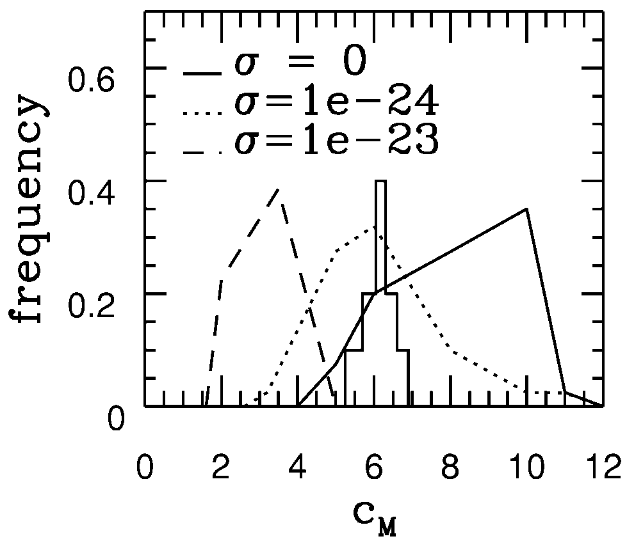

FIG. 4.—Concentration parameter c_{DM} of the coupled halos (*histogram*), for disk galaxies of any magnitudes, compared with the CDM simulations (*solid line*), and the SIDM simulations with cross sections $\sigma_{DM} = 10^{-24}$ cm^2 GeV^{-1} (*dotted line*) and $\sigma_{DM} = 10^{-23}$ cm^2 GeV^{-1} (*dashed line*) from DSSW01.

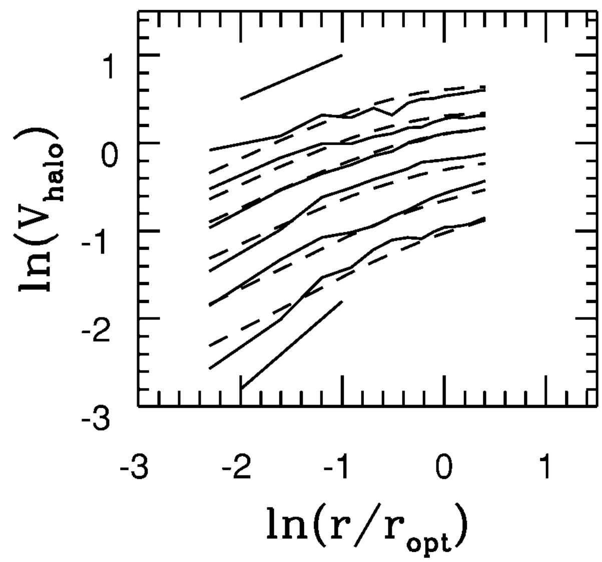

FIG. 5.—Velocity logarithmic profiles of the halos for universal rotation curves with average luminosities $\langle M_I \rangle = -23.2$ (*upper part of panel*), $\langle M_I \rangle = -22.4$, $\langle M_I \rangle = -21.2$, $\langle M_I \rangle = -20.5$, $\langle M_I \rangle = -19.4$, and $\langle M_I \rangle = -18.4$ (*lower part of panel*). The solid curves are for the halos, and the dashed curves are for the coupled models. The two short lines with slopes 0.5 and 1 are shown for comparison. The curves are shifted vertically for clarity.

is imposed. The main characteristic of the dark disk distribution, i.e., its large central hole, is indeed what is expected if this component is made of cold gas in a frozen form, which the stellar UV heating transformed into diffuse H I at the location of the stellar disk.

3.2. *The Halos*

The internal regions of halos are conveniently characterized by their concentration parameters and inner logarithmic profiles. These parameters will be used for comparing the coupled halos with CDM and SIDM halos.

3.2.1. *The Mass Concentration*

The mass concentration parameter

$$c_{DM} \equiv 27\,\frac{M(r < r_{in})}{M(r < r_{out})} \qquad (2)$$

is defined in a way similar to the simulated halos in Davé et al. (2001, hereafter DSSW01). The external radius defined by

$$r_{out} \equiv 3 \times 8.5 \text{ kpc } \frac{V_{circ}}{220 \text{ km s}^{-1}} \qquad (3)$$

in DSSW01 is very close to $1.5r_{opt}$ for an average rotation curve with $V_{circ} = 220$ km s^{-1}. As we have seen in § 2.1, the optical radius does not measure the same region of the halo in bright galaxies as it does in faint galaxies. In bright systems, the region where the power index of the velocity curve changes is between $0.5r_{opt}$ and $1.5r_{opt}$, so that in these galaxies the optical concentration parameter is measured in the region where the orbital distribution changes from isotropic to radial. In faint systems, most rotation curves are still increasing at $1.5r_{opt}$. In that case, the concentration parameter is measured almost entirely in the isotropic region. This bias is corrected by using the scale factors of the various curves relative to the brightest objects, namely, by measuring the concentration parameter between $r_{in} = 0.5r_{opt}$ and $r_{out} = 1.5r_{opt}$ for $\langle M_I \rangle = -23.1$ galaxies, between $r_{out} = 4r_{opt}$ and $r_{in} = 1.35r_{opt}$ for the faintest bin $\langle M_I \rangle = -18.4$, and the intermediate values for each bin. The advantages of this definition of the concentration parameter are that it allows one to measure directly a crucial region of the observed curves and that it is independent of the simulated model.

Figure 4 shows the histogram of the mass concentrations for the coupled halos deduced from the averaged rotation curves compared with the simulated CDM and SIDM halos from Figure 5 in DSSW01. The coupled halos are less concentrated than the CDM halos. They are well described by the SIDM halos with a scattering cross section $\sigma_{DM} \approx 10^{-24}$ cm^2 GeV^{-1}. However, because the coupled halos are degenerated and because the CDM halos have started to decline at $1.5r_{opt}$, the method overestimates this cross section.

3.2.2. *Profile Slopes*

Diagrams of halo velocities as a function of radii, plotted in a logarithmic scale to expand the region $0.1r_{opt} < r < 0.5r_{opt}$, are shown in Figure 5. There is a slow change in the inner slope with luminosity as if halos of galaxies fainter than $\langle M_I \rangle = -20.5$ have developed cores with $V_{circ} \propto r^{\sim 0.7-1}$. The radial resolution, $0.1r_{opt}$, which is $r \geq 1.3 \pm 0.3\ h^{-1}$ kpc for galaxies brighter than $\langle M_I \rangle = -21.2$ and scales approximately as $1.7(V_{circ}/220)$ kpc, is too wide for detecting cores of this order in bright systems.

The rotation curves have been inverted in order to determine the parent density distribution. In de Blok et al. (2001), we are reminded that this is a very unstable calculation. The power index of the inner density profile is plotted as a function of the radius, in physical units, for the combined sample of $\langle M_I \rangle = -18.4$ and $\langle M_I \rangle = -19.4$ galaxies in Figure 6. This corresponds to an average galaxy with a circular velocity $V_{circ} = 89$ km s^{-1}. The CDM model with $\rho \propto r^{-1.5}$ in Moore et al. (2000) does not match the data. The distribution is between an isothermal halo with a core radius $r_c \approx 1.5$ kpc, which converges too rapidly to -2 at $r > 3$ kpc, and a Navarro, Frenk, & White (1996, hereafter NFW) model with $\rho \propto r^{-1}$. The faint

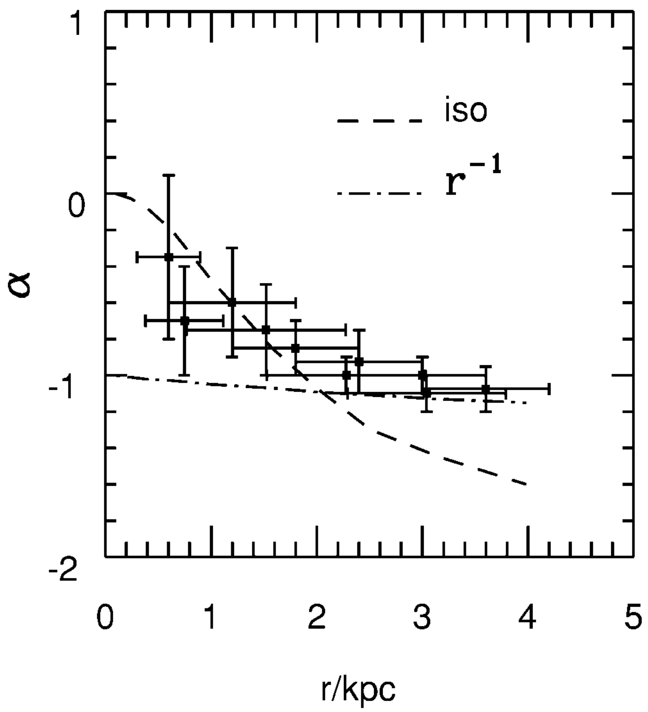

FIG. 6.—Power index α of the halo density profile plotted as a function of radius for the average galaxies with magnitudes $\langle M_I\rangle = -18.4$ and $\langle M_I\rangle = -19.4$. The power index at radius r is measured in the interval $[r - 0.1r, r + 0.1r]$ and is represented by an error bar in radius. Also shown are an isothermal halo model with core radius $r_c = 1.5$ kpc (*short-dashed line*) and an NFW model in $\rho \propto r^{-1}$ (*dash-dotted line*).

low surface brightness (LSB) galaxies in de Blok et al. (2001) have a slope $\alpha \sim -0.5$ at $0.5\ h^{-1}$ kpc and $\alpha \sim -1$ at $1\ h^{-1}$ kpc. If we combine these values and compare them with SIDM halos of various masses, a cross section of $\sigma_{\rm DM} = 10^{-24}\ {\rm cm^2\ GeV^{-1}}$ again seems adequate for describing the data.

4. DISCUSSION

Halos built with CDM alone do not match the rotation curves of faint spiral galaxies. They have too high concentrations and too steep density profiles.

Because dark matter dominates the mass profile of dwarf galaxies, it is tempting to use these objects for testing particle candidates through halo simulations. There are numerous suggestions, however, for a hidden baryonic component proportional to the H I gas (Carignan 1996) in LSB galaxies. If the dark matter in the optical region has two components, testing particle physics in such conditions is indeed premature.

In the present Letter, a dark disk component has been introduced by assuming the hypothesis of a constant collapse factor of the disk baryons relative to the halo, in bright and in faint systems. This hypothesis, used in the context of coupled halos, leads to halos having approximately the same concentration parameter, somewhat smaller than NFW models but not clearly in contradiction. There are a number of astrophysical parameters that still need to be analyzed in detail. In particular, in the tidal torque theory of angular momentum, the halos have acquired an angular momentum at the same time as the baryons. Rotating halos must be less concentrated than nonrotating ones.

In dwarf galaxies, the dark baryonic component is very large compared with the disk component. It is mostly located at a radius where it makes significant changes to the value of the concentration parameter. Its density distribution shows a hole in the central region. If this component is made of molecular hydrogen in a frozen form, presumably in a fractal hierarchy like other detected molecules, there is a stable regime in which the fractal gas is in equilibrium. Collisions between elementary cloudlets outside this regime transform cold dark gas into neutral H I. Heating by the stellar UV flux annihilates the smallest cloudlets, building a cavity in the inner region from which H I evaporates in a diffuse form. The inner tail of this distribution may change the baryonic profile in the central region, so that the measured dark profile is a combination of the halo and the dark baryons.

The dark baryonic component is weakly dissipative and therefore must be thicker than the disk. The inner Newtonian velocity due to the dark baryons depends on whether its distribution is in a flat disk or in an ellipsoid. This adds an uncertainty in the very inner velocity curve.

The best value of the scattering cross section for halo particles is $\sigma_{\rm DM} = 10^{-24}\ {\rm cm^2\ GeV^{-1}}$, which is too high for a neutralino of, say, 50–100 GeV. Compared with the CDM simulations, these theoretically predicted particles have nonzero self-scattering and annihilating cross sections and a nonzero cross section with photons, but these parameters are very small compared with the SIDM simulations.

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