THE CONSTANT DENSITY REGION OF THE
DARK HALOS OF SPIRAL GALAXIES

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ABSTRACT
We determine a crucial feature of the dark halo density distribution from the fact that the luminous matter dominates the gravitational potential at about one disk scale-length \( R_D \), while at the optical edge \( R_{\text{opt}} \approx 3R_d \) the dark matter has become the main component of the galaxy density. From the kinematics of 137 spirals we find that the DM halo density profiles are self-similar at least out to \( R_{\text{opt}} \) and show core radii much larger than the corresponding disk scale-lengths. The luminous regions of spirals consist of stellar disks embedded in dark halos with roughly constant density. This invariant DM profile is very difficult to reconcile with the fundamental properties of the density distribution of CDM halos. With respect to previous work, the present evidence is obtained by means of a robust method and for a large and complete sample of normal spirals.

1 INTRODUCTION

Rotation curves (hereafter RCs) of spiral galaxies do not show any Keplerian fall-off: this implies the presence of an invisible mass component (Rubin et al. 1980; Bosma 1981; see Salucci and Persic, 1997). More precisely, the mass distribution of stars and gas does not match that of the gravitating matter (Persic and Salucci 1988, Persic, Salucci and Stel, 1996, hereafter PSS, see also Corbelli and Salucci, 1999); the discrepancy increases with increasing radius and, at a given radius measured in units of disk length-scales \( R_d \), it increases with decreasing galaxy luminosity (Persic & Salucci 1988, 1990a,b; Broeils 1992).

Each individual circular velocity \( V(R) \) and the spiral Universal Rotation Curve can both be represented, in the optical regions, by a linear law: (Rubin et al. 1980, see Persic & Salucci...
(1991) and PSS for details)

\[ V(R) \simeq V_{\text{opt}} \left[ 1 + \nabla \left( \frac{R}{R_{\text{opt}}} - 1 \right) \right] \quad 0.4 \lesssim R/R_{\text{opt}} \lesssim 1.2 \]  

(1a)

where \( R_{\text{opt}} = 3.2 R_d \), \( V_{\text{opt}} \equiv V(R_{\text{opt}}) \), and

\[ \nabla(V_{\text{opt}}) = 0.10 - 1.35 \left( \log \frac{V_{\text{opt}}}{200 \text{ km/s}} \right)^{1.35} \]  

(1b)

In (1b) the range is \(-0.1 \leq \nabla \equiv \frac{d \log V(R)}{d \log R} \bigg|_{R_{\text{opt}}} \leq 0.7\) and the r.m.s. is 0.05 (see PSS and Fig 1)). Notice that we will freely interchange luminosities and \( V_{\text{opt}} \equiv V(R_{\text{opt}}) \), given their high degree of correlation.

The analysis of the URC and/or of individual RC has provided crucial knowledge on the main global properties of the dark and luminous matter (e.g. Salucci & Persic, 1997). On the other hand, to investigate the local properties of the dark halos (e.g. the central density) is quite difficult, especially for luminous matter (LM) dominated objects (van Albada et al 1985, but see the exception of high-resolution RC’s, Borriello and Salucci, 2000). However, as a result of recent substantial observational and theoretical progress, a proper investigation of the spiral’s halos mass structure is now possible. In fact, from the study of a large number of high-quality RC’s recently available (Persic & Salucci, 1995) it has emerged that:

i) the dark matter follows a regime of Inner Baryon Dominance (IBD) according to which in every normal spiral there is a transition radius \( R_{\text{IBD}} \)

\[ R_{\text{IBD}} \leq 2 R_d \left( \frac{V_{\text{opt}}}{200 \text{ km/s}} \right)^{1.2} \]  

(2)

inside which the luminous matter totally accounts for the whole mass distribution (see Ratnam and Salucci 2000, Salucci and Persic 1999ab, Salucci et al, 2000). This allows us to address the issue of the degeneracy problem raised by Van Albada, et al. (1985): the URC (and individual rotation curves) do show, in their profile, the kinematical signature of a transition between an inner LM-dominated region and an outer DM-dominated one (e.g. Salucci and Persic, 1999b).

ii) dark halos are distributed very differently from the various ”luminous” components (Corbelli and Salucci, 1999).

These findings allow us 1) to improve the determination of the disk mass to the level required for investigating the DM distribution and 2) to relate the dark halos around galaxies to collision-less non-baryonic cosmological structures.

* We take \( R_{\text{opt}} \) as the reference disk scale to follow PSS. We can use any other multiple of \( R_d \) to specify the URC: no result of this paper changes. The URC for the whole range of available data, \( 0.1 R_{\text{opt}} \leq R \leq 2 R_{\text{opt}} \), is given in PSS.
The aim of this letter is to derive, for a large and complete sample of spirals, the density profile of the dark halos at the edge of the disks which are embedded in them and reveal dark constant-density regions of obvious cosmological importance. The evidence for core radii of DM halos, obtained so far by means of mass modeling of a (small) number of DM-dominated RC’s (e.g. Flores and Primack 1994, Moore 1994, Burkert 1995), is being questioned in the light of the intrinsic uncertainty of the analysis itself (Burkert and Silk, 1997, van den Bosch 1999). In many cases, in fact, the standard RC fitting method has difficulty in discriminating a NFW (Navarro, Frenk and White, 1996) density profile, which has \( V_h(R) \propto R^{1/2} \) in the center, from a constant-density one, with \( V_h(R) \propto R \).

We tackle this issue by resorting to the method of Persic and Salucci (1990b) in which the power law slope of the dark halo velocity at the disk edge is derived by means of a robust and straightforward procedure, which ultimately exploits the fact that, at \( \sim R_{opt} \), the dark halo is always the main density component, even when it is a negligible mass component at about \( R_D \). ⋆

In detail, the goal of this letter is to detect a clear and reliable feature of the dark matter distribution, relevant on its own and (probably) at variance with the structural properties of standard CDM halos. Let us stress that the issue of establishing the actual CDM halo properties, or that of investigating whether non-standard CDM scenarios may be in agreement with observations, are beyond the scope of this work.

The plan of this letter is the following: in section 2 we describe the RC sample and we derive the local DM slope \( \nabla_h \) for all of the objects, in section 3 we compare the observed halo mass distributions with the CDM prediction and comment on our main results.

2 THE HALO MASS DISTRIBUTION AT \( R_{OPT} \)

Let us start from the condition of rotational equilibrium:

\[
V^2(R) = V^2_{lum}(R) + V^2_h(R),
\]

where \( V^2_{lum}(R) = V^2_g(R) + V^2_d(R) + V^2_b(R) \), with obvious notation, is the quadratic sum of the three “luminous” components: gas, disk, and bulge. We define \( \beta \equiv \frac{V^2_{lum}(R)}{V^2(R)} \bigg|_{R_{opt}} \) and \( \beta_d \equiv \frac{V^2_d(R)}{V^2(R)} \bigg|_{R_{opt}} \). In late type spirals, the exponential thin disk (of mass \( M_d \)) is by far the

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main contributor to $V_{\text{lum}}(R)$, at $R \approx R_{\text{opt}}$ (e.g. Verheijen, 1997; Rhee, 1997; Persic, Salucci & Ashman, 1993), and so

$$\beta \simeq \beta_d$$

with:

$$V_d^2(x) = \beta_d V_{\text{opt}}^2 x^2 \frac{(I_0 K_0 - I_1 K_1)|_{1.6x}}{(I_0 K_0 - I_1 K_1)|_{1.6}}$$

where $x = R/R_{\text{opt}}$, $I_n, K_n$ are the modified Bessel functions of $n$th-order, and using the previous definitions, $V_h^2(R_{\text{opt}})$, the DM velocity contribution at $R_{\text{opt}}$ is given by

$$V_h^2(R_{\text{opt}}) = (1 - \beta)V_{\text{opt}}^2$$

Let us define:

$$\nabla_d \equiv \left. \frac{d \log V_d(R)}{d \log R} \right|_{R_{\text{opt}}}$$

and $\nabla_h, \nabla_g, \nabla_b$ in the same way of the l.h.s of equation (6a) when $V_d$ is substituted by $V_h, V_g$ and $V_b$ (the subscripts $h, g, b$ refer to halo, gas and bulge respectively). In view of
the argument $ii)$ in the previous section, we can identify $V_h(R)$ with the contribution of a non-baryonic dark component.

From the previous eqs.

$$\nabla_{lum} = \left( \frac{V_d(R_{opt})}{V_{lum}(R_{opt})} \right)^2 \nabla_d + \left( \frac{V_g(R_{opt})}{V_{lum}(R_{opt})} \right)^2 \nabla_g + \left( \frac{V_b(R_{opt})}{V_{lum}(R_{opt})} \right)^2 \nabla_b$$

(6c)

For a bulge-less gas-free spiral,

$$\nabla_{lum} = \nabla_d = -0.273$$

from eqs. (4) and (6a). In this case, given its definition and the self-similarity of spiral disks, $\nabla_{lum}$ is strictly a constant. The contribution of bulge to $\nabla_{lum}$ can be totally neglected (see Persic, Salucci and Ashman, (1993) for details) while that of the gaseus disk can be evaluated in spirals with HI measurements: in a large sample (Rhee, 1997) we find that typically \( \left( \frac{V_b(R_{opt})}{V_{lum}(R_{opt})} \right)^2 \simeq 3 - 6 \times 10^{-2} \), and $\nabla_g \simeq 0.5$ that leads to $\nabla_{lum} \simeq 0.9 \nabla_d$. For a sub-sample of the present sample we have (PSS):

$$\nabla_{lum} = -0.24 \pm 0.03(2\sigma)$$

(7b)

It is worth to stress that no result of this paper changes 1) by assuming $\nabla_{lum}$ according to eq (7a) rather than to eq (7b), or 2) by neglecting the (small) variance of $\nabla_{lum}$ among spirals.

By differentiating eq. (3a) we arrive to (Persic & Salucci 1990b):

$$\nabla_h = \frac{-\beta \nabla_{lum} + \nabla}{1 - \beta}$$

(8)

which expresses the DM halo velocity slope in terms of the RC slope and of the LM mass fraction at $R_{opt}$.

Note that, for high-quality RC’s ($\delta \nabla < 0.05$), the estimate of $\nabla_h$ from eq (8) is very robust. In fact, in DM dominated objects, ($\beta < 0.5$), the uncertainties on $\beta$ do not affect the estimate of $\nabla_h$, while in LM-dominated objects, ($\beta > 0.5$), a reasonably good knowledge of $\beta$: $\delta \beta < 0.1$ suffices to estimate $\nabla_h$ within a reasonable uncertainty (i.e. $\delta \nabla_h < 0.2$).

Once we include the radial dependences of all the quantities, eq (8) is in principle valid at any radius. However, for $R < R_{opt}$, $\beta(R) \to 1$ very quickly, so that even a small error in $\beta$ or $\nabla$ will strongly affect the estimate of $\nabla_h(R)$. On the other hand, for $R > R_{opt}$, the number of available RC’s rapidly decreases.

The sample of RC’s we use in this letter is presented in PSS and Salucci and Persic (1997). It includes 131 rotation curves of spirals and 6 for dwarfs, all with a reliable profile out to $R_{opt}$. This has been ensured by the following selection criteria: each RC (a) extends out to a $R \geq R_{opt}$; (b) has at least 30 velocity measurements distributed homogeneously with radius
and between the two arms; and (c) shows no asymmetries or non-circular motions. For 21-cm RCs we require that the beam-size should be $\leq 1/2R_d$ in order to limit the uncertainties due to beam smearing. Incidentally, no LSB RC is found to satisfy these conditions, and this points to an intrinsic difficulty in studying these objects.

The values of the $\nabla'$s are estimated by fitting with eq (1) each of the 137 RC’s of the sample: the related uncertainty is small: $\delta \nabla \sim 0.02 - 0.05$; the values of $V_{opt}$, $\nabla$ and $\delta \nabla$, are given in Tables 1 and 3 of PSS and shown in Fig (1) as function of $V_{opt}$. It is worth to point out that (a) the range of $\nabla$ along the luminosity sequence is large, $\sim 0.7$, while, the corresponding r.m.s., at a given luminosity is small $< 0.1$: the DM properties are likely to vary with galaxy global properties rather than random, (b) we do not assume the URC (i.e. eq. (1b)); the values of $\nabla$ are derived from each RC.

The LM fraction $\beta$ is derived as in Salucci and Persic (1999a), Salucci et al. (1999) and Ratnam & Salucci (2000), i.e. by fitting the inner parts of each rotation curve, ($0 \leq R \leq R_{IBD}$), with (only) the circular velocity of an exponential thin disk given by Eq. (4). In this region, the only-disk mass model reproduces, with no free parameters, the normalized rotation curve $V(R)/V_{opt}$ and, with a suitable choice of the parameter $\beta$, the full curve $V(R)$. This is shown for coadded RC’s in Figure (3) and for individual RC’s in Salucci et al., (2000) and in Ratnam and Salucci (2000)). The excellent match we always

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find leads to very precise determinations of $\beta$’s; in fact, the $1 - \sigma$ fitting uncertainties are quite modest, $\delta \beta \simeq 0.05 - 0.03\beta$. Let us notice that the present method does not assume a "maximum disk" solution, rather, it is intimately related with the idea that the mass distribution in spirals follows the regime of Inner Baryon Dominance proposed by Salucci & Persic, (1999b) and then supported by Ratnam & Salucci, 2000 and Salucci et al, 2000. Finally, the present method computes $\nabla_h$ independently of the value of the disk mass-to-light ratio whose uncertainty, large in DM-dominated objects, is therefore irrelevant for the aim of this work.

The disk mass fraction $\beta$ correlates tightly with $\nabla$ (see Fig (2)). In addition, at a fixed $V_{opt}$, part of its scatter originates from observational errors and then it is unrelated to a cosmic variance of the halo mass distribution. In any case, conservatively, we derive the r.m.s. of the above relation by performing the usual least squares fit

$$\beta = 0.75 - 0.95\nabla \quad \text{r.m.s.} = 0.05$$

A relationship like eq. (9) has been found from the mass modelling of (smaller samples of) spirals (e.g. Persic and Salucci 1988; 1990a; 1990b); it can be considered as the basic law of the dark-luminous coupling in galaxies (see Salucci, 1997).

We derive the values of $\nabla_h$ for the objects of our sample by setting $\nabla_{lum} = -0.24$ and inserting in eq (8) the corresponding values of $\beta$ and $\nabla$. In Fig (4) they are plotted as a function of $\log V_{opt}$: we immediately realize that $\nabla_h$ is roughly constant over the whole sample and it shows no systematic variations along the luminosity sequence. Such variations, if present, should have clearly appeared given the high-precision measurement of $\nabla_h$. In fact the uncertainties $\delta \beta < 0.04$ on $\beta$ propagate into eq (8) in a modest way, as it can be realized by differentiating eq (8) and combining it with eq (9) to get $\delta \nabla_h \simeq (0.25 + \nabla)^{-1}\delta \beta < 0.1$

The average value found for $<\nabla_h> = 0.8 \pm 0.06$ indicates that, at $R_{opt}$, the halo RC is steeply increasing, marginally compatible with a solid body law, $V_h \propto R$. Consequently, around $R_{opt}$, the halo density must decrease with radius less steeply than $R^{-0.4}$. By assuming a pseudo-isothermal density distribution, $\rho_h(R) \propto (R^2 + a^2)^{-1}$, it follows that $a > 1.3 R_{opt}$, i.e. a core radius significantly larger than $R_d$, the size of region where the bulk of the stellar component is located.

We stress the robustness of this result by noticing that, from eq (8), crucially lower values of $\nabla_h$ (i.e. $\nabla_h < 0.5$) are possible only in the particular combination of a "flat" RC, (i.e.

$\delta$ Since $M_d = 1.1G^{-1} \beta_d V_{opt}^2 R_{opt}$ this is $\sim (\beta + \delta \beta)/(\beta - \delta \beta)$
for $\nabla < 0.2$) and a ”light disk” (i.e. $\beta < (0.5 - \nabla)/0.77 \equiv \beta_{0.5}$). Also this extreme case, however, must be ruled out since such a flat RC cannot be fitted by a mass model with $(\beta, \nabla_h)$ less than or equal to $(\beta_{0.5}, 0.5)$. (Salucci and Persic, 1999b).

3 DISCUSSION

We have investigated the mass distribution of DM halos for a large number of spirals in a way which is complementary to the mass modeling of DM-dominated rotation curves. This method has been applied to RC’s of galaxies of all luminosities, including the most luminous ones for which the standard mass modeling is quite uncertain. In detail, for each halo we have derived a single but most crucial structural property, namely, its velocity slope at $R_{opt}$.

The results are impressive: the halo mass profiles at $R_{opt}$ turn out to be $i)$ independent of the galaxy properties, $ii)$ Universal and $iii)$ essentially featureless in the sense that for any spiral the stellar disk is embedded within a constant density sphere.

High-resolution simulations and analytical studies of the Cold Dark Matter scenario have pointed to a universal halo density profile (Navarro, Frenk and White, 1996) $\rho_{CDM}(R) \propto R^{-1}(R + R_s)^{-2}$, with $R_s$ being a function of the dark halo mass $M_{200}$, of the assumed cosmological parameters, and of the red-shift of formation of the halo. Moreover, halos with identical values of the above quantities, can still have different $R_s$ if formed at various red-shifts and/or assembled through different merging histories. In detail, the circular velocity of a CDM halo is given by:

$$V_{CDM}(x)^2 \propto x^{-1}(-cx/(1 + cx) + ln(1 + cx)) \quad 4 \lesssim c(\Omega_0, M_{200}) < 30$$

(8)
Dark Halo Density Profile in Galaxies

**Figure 4.** The dark halo slopes $\nabla h$ as a function of $V_{\text{opt}}$. As a comparison, in CDM $-0.1 < \nabla h \leq 0.5$

where $c$, is the concentration parameter, $x \equiv R/R_{200}$, and $R_{200}(M_{200}, z)$ is the halo virial radius defined by $4/3\pi R_{200}^3 \rho_{200} \Omega_0 (1 + z)^3 = M_{200}$.

Before proceeding further let us notice that we will test the CDM halos at $R_{\text{opt}}$, where the baryon infall has not significantly altered the original DM halo velocity profile: $R_{\text{opt}}$ is external to the region into which most of the baryons have collapsed (Blumenthal et al, 1986). Violent dark halos-baryonic matter couplings, such as those proposed by Navarro et al, (1996) and Gelato and Sommer-Larsen, (1998) can instead modify the original halo distribution everywhere; however, given the very heuristic nature of these processes, it is best to first compare the standard-infall CDM halos with the galactic halo, and then to consider the possibly emerging discrepancies in terms of new theoretical scenarios.

The highest possible value for $\nabla^{\text{CDM}} h$ is 0.5, that is achieved on the $\sim 10\,\text{kpc}$ scale only for $c < 5$ (see Bullock et al. 1999 and Navarro, 1998), i.e. for low values of the concentration parameter, a property of low-$\Omega$ universes. This value is quite inconsistent with the average value found in spiral dark halos, especially if one considers that high resolution N-body simulations converge to a maximum value of $\nabla^{\text{CDM}} h = 1/4$ (Moore et al, 1998).

Of crucial importance is also the absence of a significant scatter in the $\nabla h$ vs. $\log V_{\text{opt}}$ relationship. In fact, the CDM theory predicts that, in a very wide region centered at $\sim 10\,\text{kpc}$ and certainly including $R_{\text{opt}}$ independently of its relation with the virial radius, galactic halos with the same mass do not follow a unique velocity curve but a family of them. These can be described by a set of straight-lines with slopes varying between $-0.1$ and $+0.5$ (e.g. see...
fig 6 of Bullock et al, 1999). According to CDM the $\nabla_h - \log V_{opt}$ plane should be filled well beyond the tiny strip of Fig (4). Taken at its face value, the observational constraint variance( $\nabla_h < 0.1$) could imply, within the CDM scenario, that protospiral halos are co-eval and have similar merging histories. A second possibility may be that the disk length-scale $R_{opt}$, in units of virial radius, is strongly coupled with the structure of the dark matter halo. (e.g., Mo, Mao & White 1998; Dalcanton, Spergel & Summers 1997; van den Bosch et al. 1999, but see also Bullock et al, 1999).

The sizes of the DM core radii turn out to be very large, at least $(3 - 4)R_d$, and independent of galaxy luminosity and DM mass fraction. This may pose a problem for the suggestion that they were formed through some luminous-dark dynamical coupling and it may call or for a primordial origin for these ”warm” regions of constant density embedding the luminous matter or for some dissipative self-regulating” process.

Burkert (1995) and Salucci & Burkert (2000), from the analysis of individual RC’s and of the URC, have proposed that the DM halos around disk systems follow the distribution: $\rho_B(R) \propto (R + R_B)^{-1}(R^2 + R_B^{-2})$, i.e. an NFW profile at large radii which converges to a constant value at inner radii. The core radius, $R_B$ is found to increase from 5 kpc to 30 kpc, as $V_{opt}$ increases form 75km/s to 300km/s. This implies f or the DM halo: $\nabla_B \simeq 0.73$ almost independently of $V_{opt}$ and in very good agreement with the halo slope determinations of fig (3).

Then, since the derived density distribution of galaxy halos is quite different from the theoretical one out to the outermost velocity data available (see also Corbelli and Salucci, 1999; Salucci & Burkert, 2000), we should seriously begin to consider the possibility that cosmological processes have cut the link between the initial conditions and the present-day galaxies properties.

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