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ΛCDM and the distribution of dark matter in galaxies: A constant–density halo around DDO 47

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Abstract. In this paper we present a test case for the existence of a core in the density distribution of dark halos around galaxies. DDO 47 has a rotation curve that increases linearly from the first data point, at 300 pc, up to the last one, at 5 kpc. This profile implies the presence of a (dark) halo with an (approximately) constant density over the region mapped by data. This evidences the inability of standard Λ Cold Dark Matter scenario to account for the dark matter distribution around galaxies, and points toward the existence of an intriguing halo scale–length of homogeneity. This work adds up to the results of Blais-Ouellette et al. (2002), Trott & Webster (2002), Binney & Evans (2002), de Blok & Bosma (2002) and Bottema (2002) in suggesting that at galactic scales CDM theory should incorporate, as an intrinsic property, a "density core" feature.

Key words. cosmology: dark mater – galaxies: spiral – galaxies: formation

1. Introduction

Rotation curves (RC's) of disk galaxies are the best probes for dark matter (DM) on galactic scale. Although much progress has been made over the past 20 years, it is only very recently that we start to shed light on crucial aspects of the DM *distribution*. Initially, the main focus was on the presence of a dark component; this later shifted to investigating the ratio of dark to visible matter (see Salucci & Persic 1997). Today, the focus is mainly on the actual density profile of dark halos (e.g. Salucci 2001) A cored distribution, i.e. a density profile flat out to a radius that is a significant part of the disk size, has been often adopted (e.g. Carignan & Freeman 1985), although the implications of this distribution appeared only after that cosmological N–body simulations found that Cold Dark Matter (CDM) virialized halos achieve a cuspy density profile (Navarro et al. 1995, hereafter NFW):

$$\rho_{\rm CDM}(r) = \frac{\rho_{\rm s}}{x(1+x)^2} \tag{1}$$

where $x = r/r_{\rm s}$, $r_{\rm s}$ and $\rho_{\rm s}$ are the characteristic inner radius and density and the simulations' spatial resolution has recently reached $\frac{1}{10}r_{\rm s}$. The halo virial radius $R_{\rm vir}$ is the radius within which the mean halo density is $\Delta_{\rm vir}(z)$ times the mean cosmic density at that red shift z (see Bullock et al. 2001). The virial mass $M_{\rm vir}$ and the corresponding virial velocity are related by: $V_{\rm vir}^2 \equiv GM_{\rm vir}/R_{\rm vir}$. The concentration parameter is defined by $c \equiv R_{\rm vir}/r_{\rm s}$. With the above definitions, the NFW circular velocity can be written as:

$$V^2_{\rm CDM}(r) = V^2_{\rm vir}\frac{c}{A(c)}\frac{A(x)}{x} \tag{2}$$

where $A(x) = \ln(1+x) - x/(1+x)$.

Numerical simulations show that in CDM halos the virial mass, the virial radius and the concentration are mutually related: objects considered at $z = 0$ within the cosmological scenario with $\Lambda = 0.7$, $\Omega_0 = 0.3$ and $h = 0.7$ have:

$$c \simeq 21\left(\frac{M_{\rm vir}}{10^{11}\ M_\odot}\right)^{-0.13} \quad R_{\rm vir} \simeq 120\left(\frac{M_{\rm vir}}{10^{11}\ M_\odot}\right)^{1/3}\ {\rm kpc} \tag{3}$$

(Wechsler et al. 2002). By applying the above to a reference mass of $5\times10^{10}\ M_\odot$, reasonable for DDO 47, we get: $c \simeq 22$ and $r_{\rm s} \simeq 4$ kpc, that are very solid guesses in view of the weak mass dependence of these quantities. The available HI data, for DDO 47 then, map exactly the region in which a NFW halo changes its velocity slope from 0.5 to 0. The relationship (3) frames the ΛCDM halo around DDO 47, but will not enter in the crucial evidence we bring for ΛCDM; that, in fact, will concern the theory at the most fundamental level of Eq. (2).

Discrepancies between the universal profile of CDM and the mass distribution of the dark halo as inferred from the RC has emerged a few years ago (Moore 1994) At the present, the existence of a crisis for CDM is seriously considered (Blais-Ouellette et al. 2002; Trott & Webster 2002; Binney & Evans 2002; de Blok & Bosma 2002; Bottema 2002),

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Send offprint requests to: P. Salucci, e-mail: `salucci@sissa.it` but the opposite view is also claimed (van den Bosch et al. 2000; Primack 2002) and so as the view for which NFW halos fare badly but not worse than other profiles (Jimenez et al. 2002).

Our previous works approached the issue in two complementary ways: *i)* we derived the accurate mass structure of halos around galaxies and then tried to fit them inside the CDM scenario (Borriello & Salucci 2001) and *ii)* we tested strategic CDM features by means of appropriate available kinematical data (Salucci 2001).

The recent HI data (Walter & Brinks 2001, hereafter WB01) and *I*–band surface brightness photometry (Makarova et al. 2002) relative to the dwarf galaxy DDO 47 give the opportunity to combine these two approaches, providing also an exemplar test case for CDM. In fact: *a)* the RC of DDO 47 extends out to ~9 disk scale-lengths, which correspond to 1.3 NFW halo scale–length r_s, at a spatial resolution of $1/7r_s$ (i.e. one disk scale-length); *b)* the HI disk surface density decreases sharply with radius: its flat contribution to the circular velocity does not mimic the solid-body profile of a constant density halo, and therefore does not complicate the mass modeling; *c)* the galaxy is of low luminosity: the content of luminous mass is small with respect to the dark one (e.g. Persic & Salucci 1988) and consequently easy to take into account.

With these favorable circumstances, we are able to correctly investigate the mass structure of the dark halo around DDO 47, and eventually to discover the inner r^{-1} signature of the NFW universal profile. Finally, we do not consider the compression exerted by baryons when they infall on dark halos, in that this process makes CDM halos density profiles even steeper than the original NFW ones (Blumenthal 1986).

DDO 47 is assumed at a distance of 4 Mpc, so that $1'' = 19.38$ pc . The crucial results of this paper do not depend on the actual value for the galaxy distance, however, we will discuss the marginal role it plays.

2. Model independent analysis

The high resolution VLA HI observations we use here are discussed in detail in WB01. In summary, multi–array VLA observations of DDO 47 give a resolution of $7.8'' \times 7.2''$ (170 pc × 140 pc) and a velocity resolution: 2.6 $\mathrm{km\,s^{-1}}$. The rotation curve, presented in WB01, is based on a moment 1 map of the HI data which has been convoluted to 30″ resolution and has been derived with the task ROTCUR in the GIPSY package (see WB01 for details). For the new analysis of this paper, we have refined the previously derived curve in WB01 by also subjecting the data to the task INSPECTOR in GIPSY. The main results are essentially the same, but now spatial and amplitude uncertainties are quantified. The best-fit parameters are summarized here: $\upsilon_{\rm sys} = 272\ \mathrm{km\,s^{-1}}$; inclination $i = 35°$; position angle PA = 310° (see WB01 for details of the fitting procedure). The data points presented in Fig. 1 are all independent measurements.

DDO 47's rotation curve (see Fig. 2) increases with radius almost *linearly*: we immediately infer that it is dominated by a dark halo (Persic & Salucci 1988, 1990) and then free from significant baryonic contributions: these, at $r > (2-3)r_{\rm d}$, would reveal themselves by causing a radial decrease or, at least, a marked deceleration in $V(r)$. The present data directly probe the gravitational potential of the dark halo inside a volume about 50 times larger than the sphere enclosing the stellar disk.

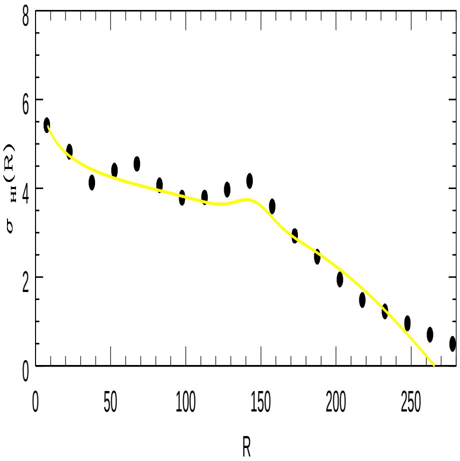

Fig. 1. The HI surface density of DDO 47 (points) with the fit used in Eq. (6) (solid line). Units are $M_\odot/\mathrm{pc}^2$ vs. arcsec.

Quantitatively, the circular velocity increases from 27 $\mathrm{km\,s^{-1}}$ at 1.5 kpc, corresponding to 2.7 $r_{\rm d}$ (and ~0.4 $r_{\rm s}$), up to 68 $\mathrm{km\,s^{-1}}$ at 5 kpc, (the farthest data point), corresponding to 9.1 $r_{\rm d}$ (and ~1.3$r_{\rm s}$). In this region, fitting linearly the velocity data, we derive the average circular velocity slope: $< \mathrm{dlog}\ V/\mathrm{dlog}\ r > = 0.80 \pm 0.06$. The CDM halo velocity slope, with an intrinsic upper limit of 0.5 at $r = 0$, predicts, for the same region, values between 0.1 and 0.3. Therefore, in DDO 47, over a radial excursions of 6 disk scale–lengths, we detect an *increase* of 600%, in V^2, that results about one order of magnitude larger than that expected for a NFW halo.

A good estimate of the *total* galaxy density $\rho_{\rm tot}$ is given, in a model independent way, by:

$$\rho_{\rm tot}(r) = \frac{V(r)^2}{4\pi G r^2}\left(1 + 2\,\frac{\mathrm{d}\log\ V(r)}{\mathrm{d}\log\ r}\right) \qquad (4)$$

at 1 kpc we get: $\rho_{\rm tot}(1) \simeq 2 \times 10^{-24}$ g/cm^3, that we compare, by means of Eqs. (1) and (3), with the density of ΛCDM halos in the mass range of $\log\ M_{\rm vir}/M_\odot = 10$–11; in all cases: $\rho_{\Lambda\rm CDM}(1\ \mathrm{kpc}) \sim 10^{-23}$, i.e. a value well exceeding that observed. This normalization of the density profile (1) implies that NFW dark halos dominate the mass distribution of galaxies with baryonic distributions like DDO 47 in a more prominent way than cored halos would do.

Thus, the CDM crisis is not only the "wrong" radial density distribution of the halos around galaxies, but especially the fact that, while we easily detect halos with a "core", we fail to detect halos with NFW "cusps". This despite that (in ΛCDM scenario) these latter should be, with respect to the luminous matter, much more prominent.

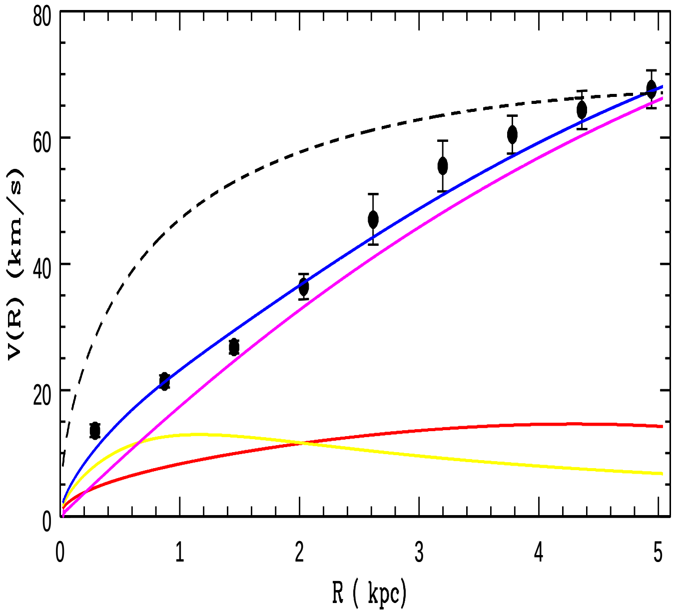

Fig. 2. DDO 47 rotation curve reproduced by the BD2 model (line through the points). Also shown (from bottom up at 5.1 kpc) the stellar, the gas and the Burkert halo distribution. Dashed line represents the ΛCDM mass model.

3. Mass modeling

The DDO 47 baryonic components are:

1) Exponential thin disk of stars of scale–length $r_\mathrm{d} = 28'' \pm 2''$, (0.54 kpc), Makarova et al. (2001), contributing to the circular velocity V as: ($y \equiv r/r_\mathrm{d}$)

$$V_\mathrm{d}^2(r) = 1.28\,\beta\, V^2(R_\mathrm{opt})\, y^2\, (I_0K_0 - I_1K_1)|_{1.6y} \qquad (5)$$

β is the disk velocity fraction at $R_\mathrm{opt} \equiv 3.2\, r_\mathrm{d}$ (for solid-body rotation curves $\beta \sim 0.1$, Persic & Salucci 1990).

2) HI disk: the HI surface density is shown in Fig. 1, the gaseous disk total mass, including the He contribution (30% of the HI mass), is about $3\times10^8\ M_\odot$; the (HI+He) contribution to the circular velocity is derived as:

$$V_\mathrm{g}^2(r) = (9.2\, r^{0.49} - 1.6\times10^{-2} r^{3.5}) D_4^2 \qquad (6)$$

where D_4 is the galaxy distance in units of the reference distance of 4 Mpc, likely ranging between 0.8 and 1.2. For $r > 3$ kpc, $V_\mathrm{g}(r)$ is approximately constant, unlike the circular velocity.

We model the mass distribution of DDO 47 with 3 components: a dark halo with a Burkert profile, a stellar disk and gaseous disk. The aim of this mass model (hereafter BD2) is to reproduce the available kinematical data, leaving to future work to derive a "global" mass model that can be extrapolated outside the range in which data are available. The density, for a Burkert halo, is:

$$\rho_\mathrm{B}(r) = \frac{\rho_0\, r_0^3}{(r + r_0)(r^2 + r_0^2)} \qquad (7)$$

where ρ_0 and r_0 are the central density and the size of the region of (almost) constant density. Then: $M_\mathrm{B}(r) = 4\, M_0\, \{\ln(1 + r/r_0) - \arctan(r/r_0) + 0.5 \ln[1 + (r/r_0)^2]\}$ with $M_0 = 1.6\, \rho_0 r_0^3$ and $V_\mathrm{B}^2(r) = G\, M_\mathrm{B}(r)/r$.

The BD2 model has 2 (really) free parameters ρ_0, r_0 and two constrained "free" parameters: D_4 and β. They are derived by χ–square minimization of the quantity $V^2(r) - V_\mathrm{d}^2(r) - V_\mathrm{B}^2(r) - V_\mathrm{g}^2(r)$ over the 9 data points. We find $\rho_0 = (1.4 \pm 0.4) \times 10^{-24}$ g/cm^3, $r_0 = 7^{+2}_{-1}$ kpc, $\beta = 0.13 \pm 0.04$, $D_4 = 0.9 \pm 0.1$. The best–fit mass model is shown in Fig. 2: the data are reproduced in an excellent way. The total disk mass results: $M_\mathrm{d} = (5 \pm 1) \times 10^7\ M_\odot$ and the halo mass inside 5 kpc $M_\mathrm{B}(5) = 5 \times 10^9\ M_\odot$ Since the RC does not reach the region where V_B starts to decelerate (i.e. when $r > r_0$), we cannot extrapolate the (dark) mass distribution outside the region directly mapped by data.

It is illustrative to show the "best" mass model for the ΛCDM scenario. We know a-priori that it will not be successful in representing the data because NFW halos have a density profile intrinsically inconsistent with that of the dark halo around DDO 47. It is worth, however to qualify the discrepancy: in Fig. 2 we report the ΛCDM mass model with the dashed line, $V_{\Lambda\mathrm{CDM}}$ has only a free parameter, the virial mass that we fix by matching the model with the outermost velocity data: $M_\mathrm{vir} = 4\times10^{10}\ M_\odot$. Notice that there are not appreciable changes by including the gas and the stellar disk contributions. The discrepancy of the CDM velocity model with the ever–rising RC data (see Fig. 2) needs not commenting; it is however instructive to look at one particular aspect of the failure of ΛCDM: let us derive its density at $r = 5$ kpc, the radius where we matched model and data. From Eq. (1) we get a value of 2×10^{-25} g/cm^3, *smaller* than the corresponding model-independent one. CDM theory shows, then, a global inconsistency with data which is well beyond a local disagreement: we can describe it as CDM bringing in the "cusp" region much more dark mass than expected, while leaving the region outside the "cusp" with a mass deficit.

We conclude this section by stressing the main result obtained: we start from the rising circular velocity of DDO 47: $<$ dlog V/dlog r $>$ = 0.80 ± 0.06. Moreover we find that, out to 9 disk-scalenghts, the slope of the dark halo contribution to V, dlog V_h/dlog r = (dlog ρ/dlog r + 2)/2, is steeper, dlog V_h/dlog r = 0.90 ± 0.03, due to small baryonic components that induce a slight deceleration in the rotation curve. On the other side, ΛCDM mass modeling of DDO 47, in the same region, yields to an unacceptably shallower halo velocity profile: dlog $V_{\Lambda\mathrm{CDM}} = 0.2 \pm 0.1$. Thus, mass modeling widens the model-independent discrepancy between the dark halo around DDO 47 and ΛCDM NFW halos discussed in the previous section.

4. Conclusions: An intriguing evidence

We think that ΛCDM NFW halos have lost, in DDO 47, the last call to represent the dark matter around galaxies. This galaxy, in fact, in terms of extension, spatial resolution, regularity and smallness of the observational errors of the rotation curve and in terms of the large dark-to-luminous mass and r_s/(spatial resolution of rotation curve) ratios, is a perfect laboratory to detect a NFW halo by pin-pointing the density slope change, from 0.5 to about 0, that should occur exactly in the region mapped by data. Saying it plainly, DM halo density of DDO 47, out to 9 r_d, is instead fully and uniquely determined by two parameters, a core density and a core radius, that are *not even existing* in the gravitational instability/hierarchical clustering Cold Dark Matter scenario.

To reconcile the ΛCDM theory with this evidence is clearly beyond the scope of this paper, let us however just indicate two possible routes: 1) the (gravitational) physics of the collapse of the innermost 10% of the halo mass distribution could be more complex than that modeled by current CDM simulations; 2) a (yet) unknown physical process could occur in the innermost 10^{-3}% of the dark halo volume, cutting down the post–collapse DM density by 1–2 orders of magnitudes.

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