The Astrophysical Journal, 634:L145–L148, 2005 December 1

THE DWARF GALAXY DDO 47 AS A DARK MATTER LABORATORY: TESTING CUSPS HIDING IN TRIAXIAL HALOS

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Received 2005 June 22; accepted 2005 October 19; published 2005 November 22

ABSTRACT

We present an analysis of high-resolution H I data of the dwarf galaxy DDO 47, aimed at testing the hypothesis that dark halo triaxiality might induce noncircular motions resulting in rotation curves best fitted by cored halos, even if the dark matter halo is intrinsically cuspy. This hypothesis could be invoked in order to reconcile the predictions of the standard ΛCDM theory with the rotation curves of disk galaxies. DDO 47 is an ideal case to test this hypothesis because it has a very regular velocity field, its rotation curve is best fitted by a cored halo, and an NFW halo is inconsistent with the data. We analyze the velocity field through the higher order harmonic terms in order to search for kinematical signatures of alleged noncircular motions needed to "hide" a cusp: the result is that globally noncircular motions are at a level of 2–3 km s^{-1}, and they are more likely to be associated with the presence of some spiral structure than with a global elongated potential (e.g., a triaxial halo). These noncircular motions are far from being sufficient to account for the discrepancy with the ΛCDM predictions. We therefore conclude that the dark matter halo around the dwarf galaxy DDO 47 is truly cored and that a cusp cannot be hidden by noncircular motions.

Subject headings: dark matter — galaxies: dwarf — galaxies: individual (DDO 47) — galaxies: kinematics and dynamics

1. INTRODUCTION

A fundamental prediction of the cosmological (Λ) cold dark matter (ΛCDM) theory is that virialized dark matter halos should have universal density profiles. An empirical fit formula for the spherically averaged density distribution $\rho(r)$ had been proposed by Navarro et al. (1996, 1997, hereafter collectively NFW),

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, \quad (1)$$

where the two parameters ρ_s and r_s are in principle free, but for a given cosmological model they are strongly correlated. This density distribution converges to power-law functions at small radii ($\rho \sim r^{-1}$) and at large radii ($\rho \sim r^{-3}$). Moore et al. (1999) later on argued that the inner cusp may even be steeper with $\rho \sim r^{-1.5}$.

The power-law behavior has been a matter of strong debate. Recent simulations, e.g., by Power et al. (2003) and Reed et al. (2005) demonstrated that the CDM halo density profiles are better represented by a function with a continuously varying slope and with no convergence to a power-law slope at small radii. A revised fitting formula was derived by Navarro et al. (2004), where the slope at the innermost radius is about −1.2 for spiral galaxies and −1.35 for dwarfs. Merritt et al. (2005) showed that the Sérsic (1968) law fits high-resolution ΛCDM halos with a wide range of masses with a Sérsic index of $n \approx 2.4$–3, which is usually used as a good fit of the surface brightness profiles of the centers of early-type galaxies.

However, as we can typically trace rotation curves observationally in the regime of $0.1r_s \leq r \leq 2r_s$, the NFW profiles still provide a good description to the dark matter halos in galaxies.

The CDM predictions have been confronted with observations investigating the rotation curves of disk galaxies. Numerous mass models of spiral, dwarf, and low surface brightness galaxies have shown that in a large number of cases, the inferred cores of dark matter halos are much shallower than expected from the NFW fit (Flores & Primack 1994; Moore 1994; Burkert 1995; Salucci & Burkert 2000; de Blok et al. 2001; Salucci 2001; de Blok & Bosma 2002; Weldrake et al. 2003; Gentile et al. 2004). The cored density distribution (Burkert 1995),

$$\rho(r) = \frac{\rho_0}{(1 + r/r_c)(1 + r/r_c)^2}, \quad (2)$$

often fits the data very well, indicating that, in contrast to cosmological predictions, the maximum density of dark halos is finite. Donato et al. (2004) even found a strong correlation between the core radius r_c and the dynamical mass, indicating again that the observed cored dark matter halos represent a one-parameter family.

This contradiction between theoretical predictions and observations has stimulated a lot of discussions as it has the potential to provide interesting new insights into the nature of dark matter and its possible interaction with visible matter (for reviews, see Primack 2004 or Ostriker & Steinhardt 2003). In this Letter we will explore the possibility that solid-body rotation curves, which are usually interpreted as a signature of constant density cores, would arise naturally also in NFW halos as a result of a triaxial dark matter mass distribution that hides the steep central density cusp, inducing deviations from axial symmetry in the disk (e.g., Hayashi et al. 2004; see, however, Gnedin et al. 2004 and Kazantzidis et al. 2004 for the effect of baryons reducing halo triaxiality). The deviations from axial symmetry in the gas kinematics can be tested observationally with galaxies showing two-dimensional velocity fields that are clearly inconsistent with an NFW profile.

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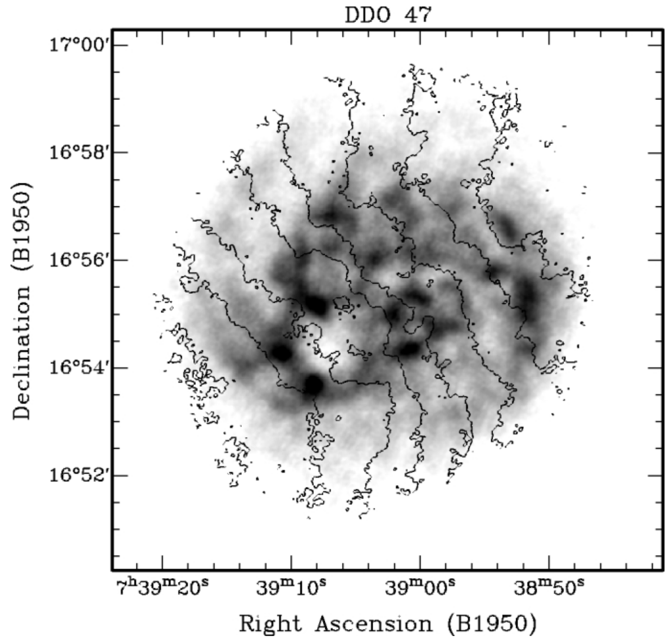

FIG. 1.—Velocity field of DDO 47 (*contours*) from the 15″ resolution cube and its total H I map (*gray scale*). Contours are spaced by 10 km s^{-1}.

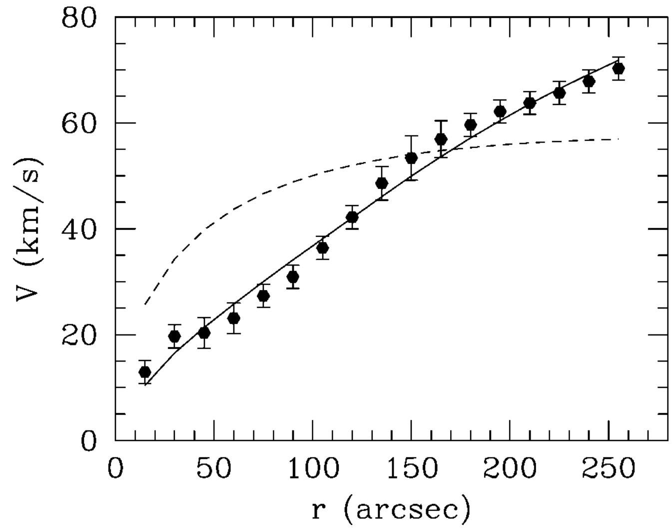

FIG. 2.—Mass models for DDO 47; the solid line is the best-fitting model with the Burkert halo, and the dashed line represents the best-fitting NFW model, with a virial mass $M_{\rm vir} = 2.4 \times 10^{10}\ M_\odot$ (see text).

2. THE TARGET: DDO 47

An ideal case is the nearby dwarf galaxy DDO 47 for which H I observations (Walter & Brinks 2001) with adequate resolution and sensitivity exist; these data show that the kinematics of the gas is very regular, with a well-behaved velocity field (Fig. 1).

DDO 47 is one of the most clear cases with kinematical properties that are inconsistent with an NFW profile. A rotation curve of DDO 47 was presented in Walter & Brinks (2001), and a more detailed decomposition, performed by Salucci et al. (2003), shows that an NFW halo is inconsistent with the data. They also show that the halo of DDO 47 has a central constant-density core: the rotation curve was successfully fitted with a Burkert halo with $r_c = 7$ kpc and $\rho_0 = 1.4 \times 10^{-24}$ g cm^{-3} (assuming a distance of 4 Mpc, and 1′ corresponds to 1.16 kpc); any other cored halo (e.g., pseudoisothermal) gives equally good fits to the rotation curve. We show the Burkert fit in Figure 2, where the rotation curve was derived by leaving the position angle as a free parameter, in order to better trace the warp. The error bars are derived from the difference between the two sides, also considering a minimum error of half the velocity resolution, corrected by the inclination. Also shown in Figure 2 is the NFW fit; differently from Salucci et al. (2003), we do not fix the virial mass $M_{\rm vir}$ by matching the last velocity point, but we leave it instead as a free parameter, the concentration parameter c scaling as $c = 21(M_{\rm vir}/10^{11}\ M_\odot)^{-0.13}$ (Wechsler et al. 2002).

Here we subject the same data to a more thorough analysis, carried out in the light of the above discussion. The spatial resolution of the data cube (~300 pc) is similar to that of the dwarf galaxy simulations performed by Navarro et al. (2004).

We have made a tilted-ring analysis of the velocity field with the inclination and the center fixed at the same values as used by Walter & Brinks (2001). As noticed by these authors, leaving the inclination i as a free parameter does not give a very stable result. In order for a possible radial change of i to account for the discrepancy with the ΛCDM predictions, i should increase as a function of radius. Instead, as is shown in Figure 3, the tilted-ring fit with the inclination free (with 35° as an initial guess) suggests that the radial change of the inclination, if any, goes in the opposite direction (i.e., i seems to get larger, not smaller, for small radii). Note that in this figure, we have fixed the position angle at an average value (separately for each radius) between fits made with different values of the inclination, between 5° and 65°. Therefore, considering that there is no evidence for an increase of the inclination, we conclude that fixing the inclination at 35° is a reasonable assumption for the aim of this Letter. We have also found that a slight change in the systemic velocity (273 km s^{-1} instead of 272 km s^{-1}) decreases the differences between the two sides.

3. HARMONIC DECOMPOSITION, NONCIRCULAR MOTIONS, AND HALO TRIAXIALITY

In order to better investigate the kinematic properties of DDO 47, we have fitted the velocity field in terms of harmonic coefficients, in which the observed velocity along the line of sight $V_{\rm los}$ is given by

$$V_{\rm los} = c_0 + \sum_{j=1}^{n} [c_j \cos(j\psi) + s_j \sin(j\psi)], \quad (3)$$

where ψ is the azimuthal angle defined as the angle from the major axis of the receding side in a counterclockwise direction. In this analysis we only considered terms up to $j = 3$. In the case of a rotating disk plus axisymmetric radial motion (i.e., the traditional tilted-ring fit of the velocity field), only terms up to $j = 1$ are present, $c_0 = V_{\rm sys}$ (the systemic velocity), $c_1 = V_{\rm rot} \sin i$ (the rotation velocity, with i being the inclination angle), and $s_1 = V_{\rm rad} \sin i$ (the radial velocity). More detailed descriptions of this method and its applications can be found in Schoenmakers et al. (1997), Schoenmakers (1999), and Wong et al. (2004).

The results of the harmonic decomposition of the velocity field are shown in Figure 4, where the parameters were fitted with a fixed inclination (35°) and the position angle left as a free parameter. First of all, we notice that the s_1 term is negligible and that the s_3 term is larger but still has a small amplitude, at most, 3 km s^{-1}. The fact that $s_3/s_1 \gg 1$ is to be expected, as DDO 47 has a low inclination and as this fraction is a strong function of inclination (Schoenmakers 1999). As shown by

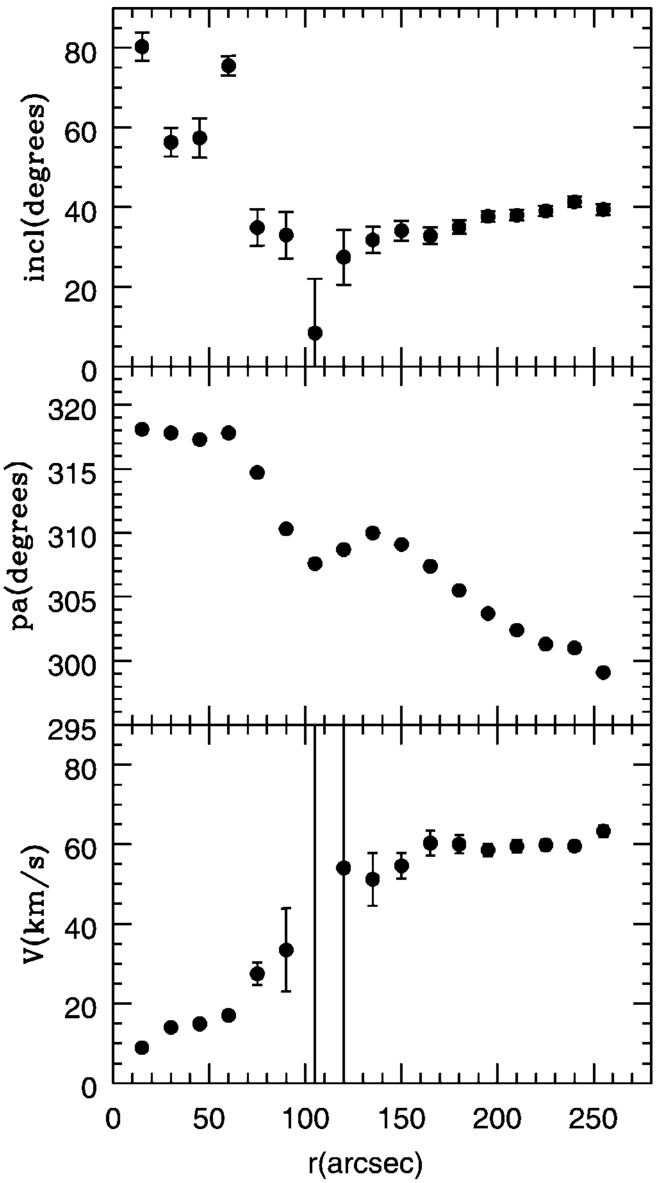

FIG. 3.—Tilted-ring fit of the velocity field with the inclination as a free parameter. *From top to bottom*: Inclination, position angle (fixed in this case; see text), and velocity as a function of radius. The uncertainties shown are formal errors.

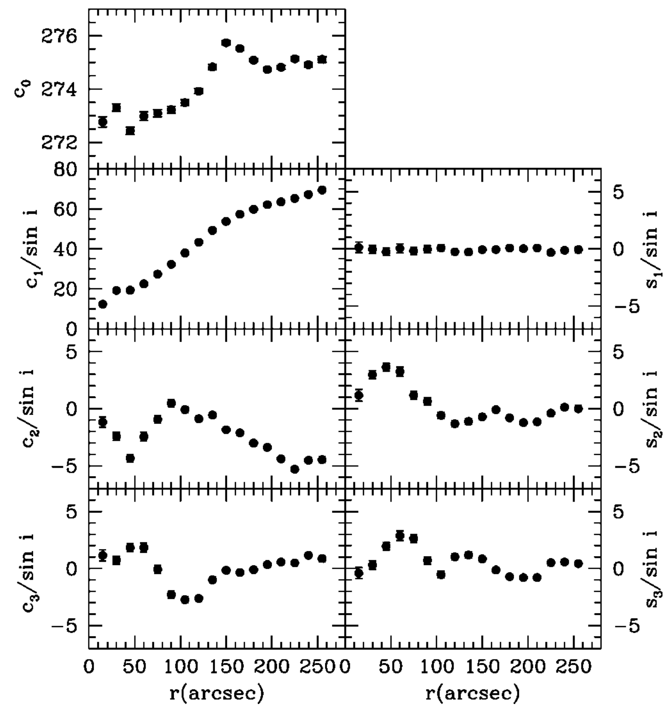

FIG. 4.—Harmonic decomposition of the velocity field, with terms up to the order 3. Notice that here the coefficients of eq. (3) with $j \geq 1$ have been divided by $\sin i$ in order to have physical velocities instead of line-of-sight velocities. The uncertainties shown are formal errors.

Schoenmakers et al. (1997), a global elongation of the potential would cause the s_3 term to be approximately constant and nonzero, while wiggles could be explained by the presence of spiral structure. In DDO 47, the latter case applies; we find no evidence for a global elongation of the potential, and the amplitude of the oscillations is much smaller (a factor of 5–10) than the discrepancy with the ΛCDM predictions. Figure 4 also shows that some lopsidedness is present, since the $j = 2$ terms are nonzero. In the residual velocity field (Fig. 5), we find that the regions with residuals larger than 5 km s^{-1} (9 km s^{-1} deprojected) are not a common feature. The innermost ones are likely to be associated with either star-forming regions or the possible bar, while the outermost ones are probably due to asymmetry in the outer warp.

As can be seen in Walter & Brinks (2001), the major axis of the stellar body seems to be a bit misaligned with the H I disk, and low-level noncircular motions associated with the optical part of the galaxy can be seen in the velocity field. Unfortunately, due to the large number of stars in the field, a more thorough analysis of the possible bar structure in the optical image is not possible. If the $s_3 \sim 3$ km s^{-1} region around 60″–70″ were associated with a barred potential, its amplitude would anyway be much lower than needed to reconcile the rotation curve with the ΛCDM predictions. We have discussed so far two of the three effects that according to Rhee et al. (2004) could bias the rotation curve (the inclination and the bar). Concerning the third effect, i.e., the influence of a possible bulge, these authors claim that the random motions of the bulge material could bias the observed rotation velocities toward the

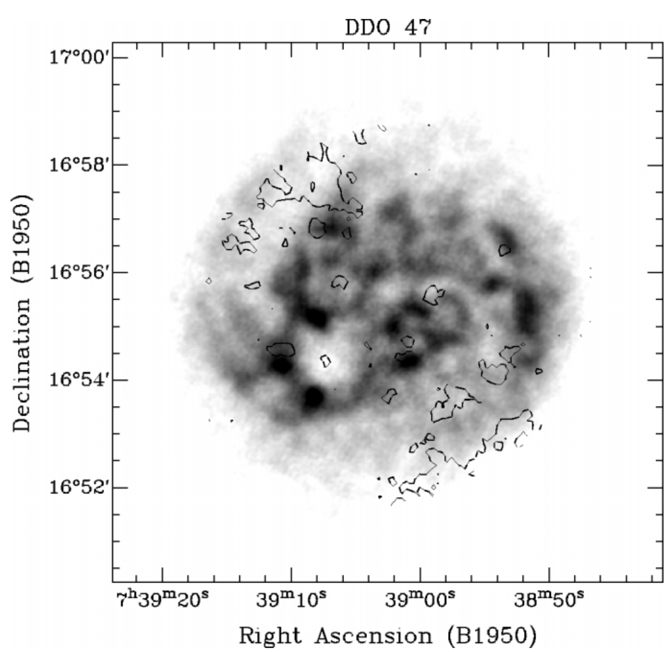

FIG. 5.—Residuals of the tilted-ring fit. Contours are −15, −10, −5, 5, 10, and 15 km s^{-1}.

systemic velocity. However, in DDO 47, visual inspection of the velocity profiles shows that they are symmetric. This was further assessed by building a velocity field where the velocity at any point is given by the peak of the profile: if the profiles were strongly asymmetric, the difference between this peak velocity field and a first-moment velocity field would be large, and the separation between the approaching and the receding side should be evident. Instead, we see small deviations and no obvious separation between the two sides.

We can therefore conclude that the noncircular motions in DDO 47 are at a level of, at most, 3 km s^{-1} and that they are not associated with a global elongation of the potential. As a particular case in Figure 6, we show the minor-axis kinematics of DDO 47: the velocity shows very small deviations from zero; the analysis performed earlier gives a more general result, making use of the whole velocity field to derive the amount of noncircular motions. We conclude that the global discrepancy between observations and ΛCDM predictions shown in Figure 2 cannot be explained by noncircular motions induced by halo triaxiality, regardless of the viewing angle.

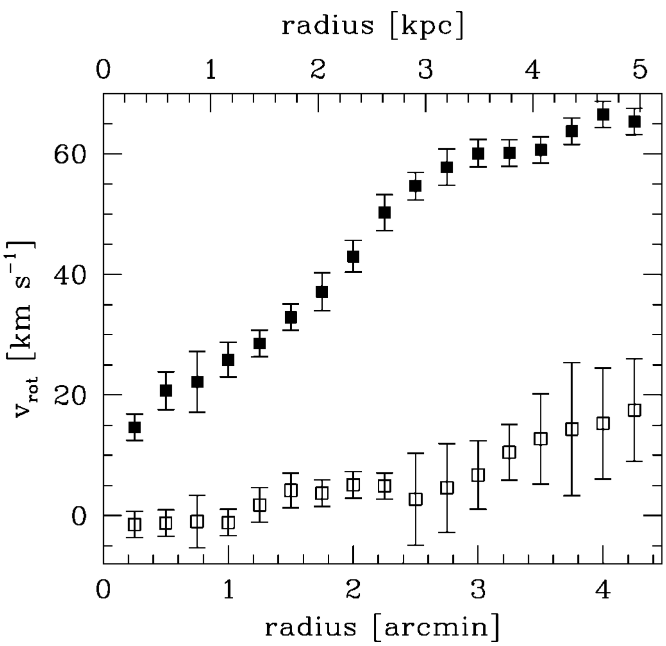

Fig. 6.—Observed rotation curves of the dwarf galaxy DDO 47 with the position angle fixed, along the major axis (*filled squares*) and along the minor axis (*open squares*). The stellar exponential scale length is 0.5 kpc.

4. CONCLUSIONS

We have presented a dynamical analysis of H I data of the dwarf galaxy DDO 47 to test the hypothesis that the possible triaxial shape of the dark matter halo might induce deviations from circular motions resulting in a rotation curve best fitted by a cored halo, with the dark matter halo being still CDM-like (i.e., cuspy). The high-quality H I observations of DDO 47 make it an ideal case to test this hypothesis because it has a very regular velocity field, its rotation curve is best fitted by a cored halo, and an NFW halo is inconsistent with the data (Salucci et al. 2003). Even though our analysis indicates a cored dark matter halo profile for DDO 47, work to test the effect of different halo shapes and disk/halo alignments on the shapes of rotation curves is clearly very valuable.

We have performed a harmonic decomposition of the velocity field in order to estimate the amount of noncircular motions. We find that they are at a level of, at most, 3 km s^{-1} and that they are likely to be associated with spiral structure rather than with a global elongation of the potential. In any case, the observed deviations from circular motion are much smaller than the discrepancy between ΛCDM predictions and the observed rotation curve. We conclude therefore that the dark matter halo around the dwarf galaxy DDO 47 is truly cored and that a cusp cannot be hidden by noncircular motions.

G. G. wants to thank E. Hayashi and O. Valenzuela for useful conversations.

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