Hα ROTATION CURVES: THE SOFT CORE QUESTION

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ABSTRACT

We present high-resolution Hα rotation curves of four late-type dwarf galaxies and two low surface brightness (LSB) galaxies, for which accurate H i rotation curves are available from the literature. Observations are carried out at Telescopio Nazionale Galileo. For LSB F583-1 an innovative dispersing element was used, the Volume Phase Holographic, with a dispersion of about 0.35 Å pixel−1. We find good agreement between the Hα data and the H i observations and conclude that the H i data for these galaxies suffer very little from beam smearing. We show that the optical rotation curves of these dark matter–dominated galaxies are best fitted by the Burkert profile. In the centers of galaxies, where the N-body simulations predict cuspy cores and fast rising rotation curves, our data seem to be in better agreement with the presence of soft cores.

Subject headings: dark matter — galaxies: halos — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

Both in physics and in cosmology we face the fundamental problem of a mass component, dark matter, which we feel confident exists because of dynamic astronomical measurements but which we have not yet detected. The only knowledge we have is that it acts gravitationally and that it dominates preferentially on large scales. It is, therefore, of particular importance to understand its properties to set guidelines in preparing more focused physics experiments to detect it.

If we wish to explore the properties of dark matter, it is necessary to select dark matter–dominated galaxies. In the nuclear regions of high surface brightness (HSB) galaxies, the baryonic component (disk and bulge) is dominant and, therefore, masks the contribution of the dark matter to the total mass distribution. In contrast, late-type dwarf galaxies provide an excellent laboratory to investigate the dark halo properties. Because of their large mass-to-light ratio $T$, and lack of prominent central bulges, these systems are thought to be dark matter–dominated at all radii.

Low surface brightness (LSB) galaxies have blue colors, low metallicities, high gas fractions, and very extended disks. The low surface brightness of these galaxies is generally interpreted as due to their higher disk angular momenta compared with that of HSB galaxies. All these properties support the idea that LSB galaxies are unevolved galaxies with low current and past star formation rates (van der Hulst et al. 1993; McGaugh & de Blok 1997). Therefore, these systems represent ideal candidates for measuring the dark matter distribution and for testing the predictions of theories of galaxy formation.

One of the main goals of current cosmology and particle physics is to determine the nature of dark matter. Currently the most popular scenario for structure formation in the universe is based on the inflationary cold dark matter (CDM) theory, according to which cosmic structures arise from small Gaussian density fluctuations composed of non-relativistic collisionless particles.

It is well known that while the CDM simulations quite nicely explain most of the observations at large scales, they face serious problems on small scales. One of the most serious discrepancies between theory and observations is related to the central dark density of dark matter–dominated galaxies, a fact put forward by Moore (1994), Flores & Primack (1994), and Burkert (1995). Navarro, Frenk, & White (1997) find, from detailed cosmological simulations, that the CDM halos have a singular central density (a cuspy core), while the observations tend to support the evidence of a constant central density (a soft core). Higher resolution N-body simulations have shown that the dark density profile is $\rho \propto r^{-1.5}$ at the center, even more cuspy than the NFW model, and hence in starker contrast to the observations (Moore et al. 1999). De Blok, McGaugh, & van der Hulst (1996) carried out 21 cm line rotation curves for a sample of LSB galaxies supporting the evidence of a soft core for these systems.

On the other hand, Swaters, Madore, & Trewella (2000) have obtained supplementary data in Hα for five LSB galaxies and argued that the low-resolution H i observations suffered from beam smearing, which smoothed the rotation curves and smeared out the effects of a strong central mass concentration. McGaugh, Rubin, & de Blok (2001) and de Blok, McGaugh, & Rubin (2001) have analyzed the same data concluding that only one of the five LSB galaxies is really affected by beam smearing. In a recent paper, van den

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Bosch & Swaters (2001) published a catalog of 20 late-type dwarf galaxies. The problem with these data is that the spatial resolution attained is too poor to distinguish the presence of soft cores. Indeed, as expected, the results of the work are nondiscriminating. Their conclusion is that there is no convincing evidence against cuspy cores of dwarf galaxy halos, but they point out that the rotation curves studied are also consistent with the presence of soft cores. However, Hα rotation curves of LSB galaxies showed in de Blok et al. (2001) are in favor of core-dominated halos.

Results by Salucci & Burkert (2000) and Borriello & Salucci (2001) confirm that most late-type dwarf galaxies are core-dominated in conflict with the cusp predicted by Salucci (2001) shows evidence for a soft core also in HSB galaxies.

On galaxy cluster scales, the presence of shallow cores for the dark halos is statistically weak, because not many galaxy clusters have yet been properly observed. On the other hand, strong lensing observations of CL 0024+1654 allow the production of a mass map of unprecedented resolution. Using these data, Tyson, Kochansky, & Dell’Antonio (1998) have shown the presence of a soft core, in conflict with the prediction of the NFW model. Recent X-ray data from Chandra for A1795 have revealed that the mass distribution of this cluster is shallow at the center indicating a soft core (Ettori et al. 2002). Firmani et al. (2000, 2001) extended the analysis of the global halo scales (core radius and central density) from H I rotation curves of core-dominated LSB and dwarf galaxies to galaxy clusters with evidence of soft cores, integrating the available information from the literature. In that early work the authors find that the central density is independent of the halo mass and that the core radius scales with the mass when the mass range is increased. One of the purposes of this work is to see if, by using a sample of Hα rotation curves, we are in agreement with their previous findings.

This paper is organized as follows: in § 2 we describe our observations and the data reduction, while in § 3 we present our rotation curves and compare our observations with earlier Hα data. The mass model and the fits of the observations are presented in § 4, with the global halo scaling relations. Our results are briefly summarized in § 5. We use \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) throughout the paper.

### 2. THE DATA

#### 2.1. Sample

The galaxies presented in this work have been selected from the sample of late-type dwarfs in van den Bosch & Swaters (2001) and from the sample of LSB galaxies in de Blok & McGaugh (1997). The properties of these galaxies are presented in Table 1, which lists the galaxy name (col. [1]), the adopted distance using \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (col. [2]), the disk scale length in kpc (col. [3]), the inclination angle (col. [4]), the position angle (col. [5]), the systemic velocity (col. [6]), the central surface brightness (col. [7]), the morphological type (col. [8]), and the references (col. [9]). The first four galaxies are late-type and dwarf galaxies, while the last two are LSB galaxies.

#### 2.2. Observations

Observations were carried out at the 3.6 m Telescopio Nazionale Galilei (TNG) in 2000 November and 2001 March. We used the DOLORES (Device Optimized for Low Resolution) instrument in spectroscopic mode with the grism HR-\( r \) [0.8 Å pixel\(^{-1}\), \( \lambda \in (6200, 7800) \) Å, and a spatial scale of 0.28 pixel\(^{-1}\)] for all the galaxies except F583-1. For this galaxy we used an innovative Volume Phase Holographic (VPH) dispersing element with 1435 lines mm\(^{-1}\) and \( \lambda_{\text{blaze}} = \lambda_{\text{HR}} \) (the dispersion was about 0.35 Å pixel\(^{-1}\)). The slit size was either 1" or 1.5”, depending on the seeing, yielding a spectral resolution of \( \sim 3 \) Å (4.5 Å) The instrumental parameters are summarized in Table 2. We used DOLORES in photometric mode for the positioning of the slit: by doing this we were able to ensure that the slit was properly aligned along the major axis of the galaxy as seen on the screen. Cumulative exposure times were half an hour, except for UGC 4325 and UGC 7603, for which they were 1 hr. All six galaxies had previously published Hα observations. For all galaxies except UGC 4325 and UGC 4499, argon comparison lamp frames were taken immediately before and after each object exposure; for UGC 4325 and UGC 4499 this was not possible because of technical problems, but this did not significantly affect the resulting rotation curves.

#### 2.3. Reductions

Red spectra of spiral galaxies at low redshifts typically show the prominent nebular lines of Hα λ6563, [N ii] λ6583, [O iii] λ5007, [O ii] λ3727, [S ii] λ6716, 6731. The prominent [O ii] λ3727 is not shown in Table 1.

### General Properties of the Galaxies

| Name          | \( D^a \) (Mpc) | \( h_b^b \) (kpc) | \( i^c \) (deg) | P.A.\(^d\) (deg) | \( v_{sys}^e \) (km s\(^{-1}\)) | \( \mu_b^f \) (m arcsec\(^{-2}\)) | Morphological Type | References |
|---------------|----------------|------------------|---------------|-----------------|-----------------|-----------------|-------------------|------------|
| UGC 4325...... | 10.1           | 1.6 (R)          | 41            | 41              | 523             | 21.6 (R)        | SA(s)m           | 1, 2       |
| UGC 4499...... | 13.0           | 1.5 (R)          | 50            | 140             | 691             | 21.5 (R)        | SABdm            | 1, 2       |
| UGC 7603...... | 6.8            | 0.9 (R)          | 78            | 197             | 644             | 20.8 (R)        | SB(s)dSp         | 1, 2       |
| UGC 11861..... | 25.1           | 6.1 (R)          | 50            | 28              | 1481            | 21.4 (R)        | SABdm            | 1, 2       |
| LSB F571-8..... | 48.0           | 5.2 (B)          | 90            | 165             | 3754            | 23.9 (B)        | Sc                | 3, 4       |
| LSB F583-1..... | 32.0           | 1.6 (B)          | 63            | 175             | 2264            | 24.1 (B)        | Sm-Irr           | 3, 4       |

- \( a \) Using \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).
- \( b \) (B) = B filter photometry; (R) = R filter photometry.
- \( c \) From Hα observations in the literature.
- \( d \) Measured positive from north to east.

References.—(1) Swaters 1999; (2) van den Bosch & Swaters 2001; (3) de Blok & McGaugh 1997; (4) de Blok et al. 2001.
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TABLE 2

| Parameter                      | Value          |
|-------------------------------|----------------|
| Spectrograph                  | DOLORES        |
| Grism                         | HR-r           |
| Spectral coverage (Å)         | 6200–7800      |
| Slit                          | 1"–1'5 × 9'4   |
| Spatial Scale (arcsec pixel⁻¹) | 0.275 (1 pixel = 15 μm) |
| Dispersion (Å pixel⁻¹)        | 0.8            |
| Resolution (FWHM) (Å)         | ~3⁴            |
| Detector                      | Loral CCD⁵     |
| CCD dimensions (pixel²)       | 2048 × 2048    |
| Field of view (arcmin)        | 9.4 × 9.4      |
| Readout noise                 | ~7 e⁻/rms      |
| Conversion Factor             | ~1 e⁻/ADU      |
| CCD QE peak (%)               | 95 at 6000 Å   |

² For a 1" slit.
⁵ Thinned and back-illuminated.

The dispersion curve. The same calibration lamps were used to model the effect of line curvature. For UGC 4325 and UGC 4499, for which we could not take Ar comparison lamp frames right before and after the object spectrum, we used the sky lines for wavelength calibration.

We checked the goodness of the wavelength calibration on the sky lines for each object spectra; that is, after calibration, sky lines should be straight (along the spatial direction) and match the laboratory wavelengths. For all the galaxies except F583-1 the 1 σ calibration velocity error was \( \delta v_{\text{cal}} \in (4, 7) \) km s⁻¹, while for the galaxy F583-1 \( \delta v_{\text{cal}} \approx 2.5 \) km s⁻¹.

After the wavelength calibration test, the sky lines and the sky background were removed by interpolating the regions above and below the galaxy emission with a second-order polynomial.

An example of a two-dimensional long-slit spectrum after reduction is shown in Figure 1 for the galaxy LSB F583-1; Figure 2 shows the exact position of the long slit on the galaxy.

2.3.3. The Rotation Curves

We measured the centroids at each position (row) along the Hα galaxy emission by making Gaussian fits to the line profile. The errors were derived by simulating realistic spectra and estimating the relation \( \delta v_{S/N} = F(S/N) \) for each spectrum; the signal-to-noise ratio (S/N) threshold was chosen such that \( \delta v_{S/N} \lesssim 25 \) km s⁻¹. The final 1 σ velocity error at each position along the major axis is therefore given by \( \delta v = [(\delta v_{\text{cal}})^2 + (\delta v_{S/N})^2]^{1/2} \).

We assumed, furthermore, that the maximum of the light in the direction perpendicular to the dispersion of the continuum spectrum would coincide with the center of the galaxy. However, in those cases where the continuum was too weak to give a reliable estimate, we used a sigmoid function to fit the unfolded rotation curve and assumed the center of symmetry to be the center of the galaxy. In other words we got an estimate of the dynamic center under the assumption of unperturbed circular motion. In all cases the fit was carried out accounting for the errors estimated as above, and the velocity of the center of symmetry was assumed to be the systemic velocity of the galaxy.

![Fig. 1.—Example of a two-dimensional long-slit spectrum after reduction: LSB F583-1](image-url)
The final rotation curves (velocity as a function of the galactocentric distance) were obtained by folding the line-of-sight velocity profiles around the estimated centers (i.e., by combining the approaching and the receding sides) after correction for the inclination of the galaxies \[ v(r) = v_{los}/\sin i \], and by re-sampling the Hα points every 1.5–3″, depending on the seeing and the Hα emission distribution (continuous or clumpy) of each galaxy.

The final \( \Delta v \) for each radial velocity point also takes into account the asymmetries in the rotation curve, which are less than 10 km s\(^{-1}\). Finally, \( \Delta v \) is given by

\[
\Delta v = \sqrt{\text{rms}_v^2 + \frac{1}{\sum_{i=1}^{N}(1/\delta v_i^2)}},
\]

where \( \text{rms}_v \) is the standard deviation of the \( N \)-velocity measurements inside the resampling bin and \( \delta v_i \) is the 1σ error of the line-of-sight velocity measurements in the bin. The \( \gtrsim 50\% \) asymmetries in the rotation curve (quite common in late-type dwarf galaxies as shown by Richter & Sancisi 1994) are taken into account in the term \( \text{rms}_v \).

The final 1σ errors for the velocities are, as expected, fairly large when compared to the H\( \alpha \) observations, except for the two galaxies UGC 7603 and F583-1. For all the galaxies, the major contribution to the final error comes from the \( \delta v_{S/N} \) term: because of the short exposure times and the intrinsic faintness of the Hα emission in these galaxies, the Hα line did not have a high enough S/N to make the term \( \delta v_{S/N} \) small. The rotation curve of UGC 7603 has instead quite small errors, due both to the higher cumulative exposure time and to intrinsically stronger Hα emission. The rotation curve of the galaxy F583-1 has very low velocity errors, due to the fact that the corresponding spectrum was taken with the new VPH dispersing element. This newly introduced upgrade in the DOLORES spectrograph allows a higher spectral resolution together with an enhanced transmission efficiency (Conconi et al. 2001).

3. COMPARISON WITH OTHER OPTICAL ROTATION CURVES

High-resolution Hα rotation curves for the two galaxies F571-8 and F583-1 have been published by de Blok et al. (2001). In Figure 3 our Hα rotation curves for these two galaxies are plotted together with the Hα rotation curves obtained by de Blok et al. (2001): for both galaxies, the two independent rotation curves agree very well within the errors.

3.1. H\( \alpha \) versus H\( i \) Data

The observed Hα rotation curves were then compared to the H\( i \) rotation curves published in literature, in order to see how strongly the H\( i \) rotation curves are affected by beam smearing and to complement the Hα curves at large distance from the center. Indeed, the spatial resolution of the H\( i \) data for the LSB galaxies (F571-8 and F583-1) is \( \gtrsim 13″ \), while the spatial resolution of the H\( i \) data for the late-type dwarf galaxies is \( \approx 30″ \). In Figure 4 we show the Hα rotation curves (this work) with the 21 cm points overplotted (de Blok & McGaugh 1997; van den Bosch & Swaters 2001).

For the three galaxies UGC 4325, UGC 7603, and UGC 11861 the Hα points agree (within measurement errors) with the H\( i \) data; for the two galaxies UGC 4499 and F583-1, the Hα velocities are slightly larger than the H\( i \) data in the inner regions, but the velocity differences are always \( \lesssim 5–10 \text{ km s}^{-1} \); only for F571-8 are the Hα velocities much larger (up to 30 km s\(^{-1}\)) than those derived from the 21 cm line.

We conclude that for five of the six galaxies in our sample, the H\( i \) rotation curves are not substantially affected by beam smearing. The only galaxy with an H\( i \) rotation curve that is apparently affected by beam smearing is F571-8. This galaxy is almost edge-on so the discrepancies could be due to differences in the optical depth and projection effects.
4. MODELING

For robust mass modeling, both good spatial resolution in the inner regions and extension of the rotation curves to large radii are necessary. The good spatial resolution in the inner regions is necessary to properly estimate the mass distribution in the nuclear region and to discriminate between cuspy or soft dark matter density cores. The extension to large radii is necessary to better constrain the total mass of the galaxy; it also helps constrain the NFW fits, whose velocities tend to keep rising if not constrained at large radii.

Because the H$_{\alpha}$ curves have good spatial resolution and the 21 cm curves go to larger radii, we combine the data to produce hybrid rotation curves. We use these hybrid rotation curves in the following mass modeling in order to see if the observed rotation curves are characterized by soft or cuspy density profiles.

The aim of this work is to test for the existence of soft cores for the observed galaxies. We want to give the NFW model a maximum chance to match the data. Thus, since for these galaxies the luminous component contribution to the gravitational potential seems not to be dominant, we assume that the observed optical high spatial resolution rotation curves trace the dark halo component. We neglect, in a first approximation, the disk contribution to the total gravitational potential. The idea is to verify if the observed rotation curves rise more gently in the inner regions than the NFW model, showing evidence of a soft core. A more accurate modeling of the rotation curve makes the conflict with the CDM models even worse.

In this approximation we apply a best-fit procedure to the data, assuming three different models for the dark halo mass distribution and, consequently, three different functions for the circular velocity:

- **The Burkert profile** (Burkert 1995),

\[
v^2(r) = 2\pi G\rho_0 r_s \frac{1}{r} \left\{ \ln \left( 1 + \frac{r}{r_s} \right) \sqrt{1 + \left( \frac{r}{r_s} \right)^2} - \arctan \frac{r}{r_s} \right\},
\]

where $\rho_0$ and $r_0$ are the central density and the core radius, respectively; this profile is characterized by a central soft density core ($\rho$ is constant at small radii), while at large radii $\rho \propto r^{-3}$.

- **The Navarro-Frenk-White (NFW) profile** (Navarro et al. 1997),

\[
v^2(r) = 4\pi G\rho_0 r_s^3 \frac{1}{r} \left[ \ln \left( 1 + \frac{r}{r_s} \right) - \frac{r/r_s}{(r/r_s + 1)} \right],
\]

where $\rho_0 = \delta_c \rho_{\text{crit}}$ and $r_s$ is a scale radius; this profile is characterized by a cuspy core ($\rho \propto r^{-1}$ at small radii), while at large radii $\rho \propto r^{-3}$.

- **The Moore profile** (Moore et al. 1999),

\[
v^2(r) = \frac{8}{3} \pi G\rho_0 r_s^3 \frac{1}{r} \ln \left[ 1 + \left( \frac{r}{r_s} \right)^{1.5} \right],
\]

where $\rho_0$ is a characteristic density and $r_s$ is a scale radius; this profile is characterized by a steeper central cuspy density core ($\rho \propto r^{-1.5}$ at small radii), while at large radii $\rho \propto r^{-3}$.

The observed rotation curves were normalized to the outermost observed points; we also normalized the three models to the corresponding maximum velocities and maximum radii ($r_{\text{max}} = 3.3 r_0$ for the Burkert profile, $r_{\text{max}} \approx 2.16 r_s$ for the NFW profile, and $r_{\text{max}} \approx 1.25 r_s$ for the Moore profile).

The observed rotation curves are shown in Figure 5 overplotted with the three models. First of all, we notice how nicely the Burkert profile follows the observed rotation curves (we must keep in mind that we did not fit the observed points, but we only normalized each curve to its last point). Second, the NFW and the Moore profiles are inconsistent with the observed rotation curves in the inner regions: they both predict a too-fast-rising rotation curve because of the presence of the cuspy cores. The natural matching of the Burkert profile to the observed rotation curves and the inconsistency in the inner regions seen when we use the two profiles predicted by the numerical simulations tell us that these six galaxies seem to be core-dominated. Third, the Moore profile is always the most inconsistent in the inner points, since considering steeper
inner density profiles only makes the inconsistency greater between the observed and the theoretical rotation curves. In this first-fit procedure, note that the NFW model and the Moore profile have normalized $\chi^2$ with large values, while low values are only obtained assuming the Burkert profile.

In the plot, the normalized $\chi^2$ are indicated in parenthesis for the three models.

A second comparison with the NFW profile for the mass distribution of the galaxies may be obtained. The NFW circular velocity as a function of the radius may be written in...
Fig. 5.—Normalized hybrid rotation curves compared to models in minimum disk hypothesis: asterisks are the H\(_\alpha\) points, open squares are the H\(_i\) data; the solid line is the Burkert profile, the dashed line is the NFW profile, and the dot-dashed line is the Moore profile. The observed rotation curves are normalized to the last observed point; the numbers in parenthesis are the normalized \(\chi^2\) for the three models; the error bars shown represent 1\(\sigma\) errors.
terms of the concentration parameter $c = r_{200}/r_s$ ($r_{200}$ is the radius of the sphere having mean density equal to 200$\rho_{\text{crit}}$) and the circular velocity at the virial radius $v_{200}$:

$$v^2(r) = v_{200}^2 \frac{1}{x} \ln \frac{1 + cx}{1 + x} - \left[ \frac{cx}{1 + cx} \right] ,$$

where $c$ and $v_{200}$ are the two free parameters of the fit and $x = r/r_{200}$.

The best-fit procedure allows us to derive the values of $c$ and $v_{200}$ of the observed rotation curves. The fitting is done by the maximum-likelihood method applied to the function:

$$\chi^2 = \frac{1}{N - m} \sum_{i=1}^{N} \frac{1}{\delta v_i} (v_i - v(r_i))^2 ,$$

where $N$ is the total number of points to fit, $m$ is the number of free parameters, $\delta v_i$ is the 1 $\sigma$ velocity error, $v_i$ is the observed velocity, and $v(r_i)$ is the model velocity.

In Tables 3 and 4 the minimum disk model best-fit values are shown for the Burkert and the NFW profiles, respectively.

The Burkert profile reproduces both the inner and the outer regions of the observed rotation curves, while the NFW profile best-fit solution does not reproduce the rotation curves as well. To obtain a good enough statistical fit with the NFW profile, we had to force the fitting procedure; we found that the best-fit solutions are characterized by too large maximum velocities, that in the best fitting maximum velocities are up to 30% higher than what is observed. Note that the outermost points of the rotation curves come from H I observations taken from the literature with errors of $\sim 3$–7 km s$^{-1}$. The galaxy UGC 4499 is the only one for which the NFW best-fit solution does not require a large maximum velocity, but this galaxy has a stellar bulge component which, even if not dominant, could make the inner profile steeper. The concentration values derived by the best-fit procedure are listed in Table 4 for the observed objects; the observed $c$-$M_{200}$ relation is shown in Figure 6, overplotted with the theoretical one predicted by the NFW model for a ΛCDM cosmology. Note that even forcing the NFW model to represent the mass distribution of the galaxies, the concentrations appear to be lower than the predicted values from the CDM Λ-body simulations. Unfortunately, the concentration values measured in the dark halos by the Λ-body simulations show a very large scatter, and no consensus is reached by different authors on the real scatter in the relation concentration-halo virial mass (or $c$-$M_{200}$; see, e.g., Wechsler 2001). Note, however, that the values inferred for the concentrations are upper limits in this minimum disk approximation. Thus, if the disk component is included in the analysis, the concentration values should be pushed down to lower values in the plot.

Regarding a comparison with other published works, the galaxies F583-1 and F571-8 are also found in the published sample of high-resolution H I rotation curves by de Blok et al.

### Table 3

| Name             | $\rho_0$ ($M_\odot$ pc$^{-3}$) | $\Delta \rho_0^a$ ($M_\odot$ pc$^{-3}$) | $r_0$ (kpc) | $\Delta r_0^a$ (kpc) | $\chi^2$ |
|------------------|-------------------------------|-----------------------------------------|-------------|---------------------|---------|
| UGC 4325......... | 0.231                         | 0.044                                   | 1.77        | 0.18                | 0.6     |
| UGC 4499......... | 0.090                         | 0.027                                   | 2.28        | 0.39                | 0.4     |
| UGC 7603......... | 0.080                         | 0.016                                   | 2.09        | 0.68                | 0.7     |
| UGC 11861........ | 0.060                         | 0.009                                   | 5.81        | 1.00                | 1.0     |
| LSB F571-8....... | 0.065                         | 0.010                                   | 5.15        | 0.33                | 0.3     |
| LSB F583-1....... | 0.035                         | 0.007                                   | 4.23        | 0.35                | 0.3     |

*a* Quoted errors are 1 $\sigma$ errors on the best-fit solution parameters.

### Table 4

| Name             | $c$     | $\Delta c^a$ | $v_{200}$ (km s$^{-1}$) | $\Delta v_{200}^a$ (km s$^{-1}$) | $\Delta \varphi_{\text{max}}^b$ (km s$^{-1}$) | $\Delta \varphi_{\text{best H I}}^c$ (km s$^{-1}$) | $\chi^2$ |
|------------------|---------|--------------|-------------------------|---------------------------------|---------------------------------|---------------------------------|---------|
| UGC 4325......... | 13.2    | 2.3          | 80                      | 7                               | 0.8                             | 14                             | 4       |
| UGC 4499......... | 8.8     | 2.5          | 70                      | 10                              | 0.5                             | 8                              | 5       |
| UGC 7603......... | 5.8     | 1.1          | 78                      | 8                               | 1.0                             | 22                             | 3       |
| UGC 11861........ | 7.4     | 1.1          | 158                     | 12                              | 1.6                             | 32                             | 7       |
| LSB F571-8....... | 8.6     | 1.3          | 136                     | 10                              | 0.5                             | 20                             | 6       |
| LSB F583-1....... | 5.4     | 1.1          | 92                      | 8                               | 0.3                             | 14                             | 5       |

*a* Quoted errors are 1 $\sigma$ errors on the best-fit solution parameters.

*b* This is the difference between the best-fit solution maximum velocity and the observed maximum velocity of the rotation curve: the higher this value, the funnier the NFW best-fit solution.

*c* This is the 1 $\sigma$ velocity error of the last observed point in the H I rotation curve.
al. (2001). For the LSB F583-1 we have a good agreement between our estimate of the central density assuming a Burkert profile as representative of the mass distribution and the minimum disk model adopted in the de Blok et al. (2001) analysis. Since the core radius estimate depends on the assumed model, and the de Blok et al. (2001) analysis uses a isothermal model, an agreement is not necessarily required. For F571-8 our estimate of the central density in this approximation is slightly lower than the de Blok et al. (2001) estimate. Because of the projection effects associated with our seeing this galaxy edge-on, we conclude that our estimates of the central densities are close to the de Blok et al. (2001) work. The two galaxies UGC 4325 and UGC 7603 are in common with the work of de Blok & Bosma (2002). For UGC 4325 there is disagreement between our estimates of $c$ and $v_{200}$ and the corresponding estimates obtained by de Blok & Bosma (2002); they find a lower value for $c$ and a higher value for $v_{200}$ than we do. For this galaxy we also find a value of $\rho_0$ for the Burkert profile that is more than twice the corresponding value found by de Blok & Bosma (2002). The two parameters $\rho_0$ and $r_0$ are related such that if $r_0$ is increased, $\rho_0$ must decrease in order to fit a given rotation curve; although $\rho_0 = 0.231 M_\odot \text{pc}^{-2}$ and $r_0 = 1.77$ kpc are the best-fit parameters for our H$\alpha$ rotation curve, it may be possible that a better rotation curve (with smaller velocity error bars and with more points in the inner region) could better constrain the two parameters, giving a larger value for the core radius and a smaller value for the central density. For UGC 7603, instead, there is quite good agreement on all the best-fit parameters for the two assumed minimum disk models.

We, therefore, conclude that the six observed galaxies, in the minimum disk hypothesis, are characterized by dark matter profiles with constant density cores and are rather inconsistent with the density profiles predicted by cosmological numerical simulations. This inconsistency is worse in the case of the Moore profile. By taking into account both the contribution of the stellar disk and the baryonic adiabatic contraction, the inconsistency between the NFW profile and the observed rotation curves gets worse.

### 4.1. Halo Adiabatic Contraction

In the last section we found that the galaxies in our sample are core-dominated. However, the values for the halo central density and the core radius were inferred by a first analysis, neglecting the disk component. They have to be considered as upper limits for the halo scales and are representative of the present dark halo. In the following section, we analyze the rotation curves, taking into account the disk contribution. The dark matter halo density profile that we infer today from observations is not the primordial one. In fact, due to the cooling of the baryons inside the virialized halo, the halo gravitational potential well is altered and the halo shrinks, becoming more concentrated in the inner regions, and forcing the matter distribution to readjust. Consequently, after the disk formation, the dark component of the rotation curve could rise more steeply in the inner regions. If our aim is to test the predictions of the current cosmological paradigm through the mass distribution of the observed galaxies, we have to take into account the halo contraction during the disk formation and correct our analysis for this effect.

Since the disk formation is a slow process, the halo contraction is assumed to be adiabatic, and we account for it by using adiabatic invariant techniques (Flores et al. 1993). A useful approximation is to assume that the angular momentum of the dark matter particles is unaffected by the baryons that are collapsing toward the center. That is, for circular motion, $r M(<r)$ is preserved, and this quantity is an adiabatic invariant during the growth of the disk. In this way, it is straightforward to predict a rotation curve reflecting the present distribution of dark matter and baryons from an initial halo profile. Accounting for the halo adiabatic contraction we can attempt to discriminate between the NFW and the King model as representative mass distribution of the primordial dark halo.

The procedure we have implemented in order to interpret the data builds a fiducial galaxy. We assume for the primordial halo a mass distribution with a soft core (described by a King model) or a cuspy core (assuming the NFW profile). The King model is assumed with a form parameter of $f_p = 8$. Although the shape of the profile in the central region is not sensitive to the form parameter, we chose to use this particular King model since the rotation curves of LSB and dwarf galaxies are well fitted by this model in the inner regions (Firmann et al. 2001).

We build the disk in order to reproduce the observed photometric data. We have our own photometric data only for UGC 4325 and UGC 4499. For the other galaxies, the photometric values of LSB F583-1 and LSB F571-8 are taken from de Blok et al. (2001) and of UGC 11861 and UGC 7603 from Swaters (1999). In Table 5 the baryonic fraction $f_b = M_{\text{disk}}/M_{\text{tot}}$ for the observed galaxies is reported with the assumed mass-to-light ratio $\Upsilon_*$ and the scale length $h$. The disk was modeled using the photometric profile with $\Upsilon_*$ for the two LSB galaxies (consistent with the $E(B-V) = 0.6$ estimated for these galaxies by de Blok et al.

| Name         | $h^a$ (kpc) | $f_b$ ($\times 10^{-2}$) | $\Upsilon_*$ | $c$ | $M_{200}$ ($\times 10^{10} M_\odot$) | $\rho_0$ ($M_\odot \text{pc}^{-2}$) | $r_0$ (kpc) |
|--------------|-------------|--------------------------|---------------|-----|-----------------------------------|---------------------------------|-------------|
| UGC 4325.....| 1.7         | 1.6                      | 1.0           | 15.1 $\pm$ 0.5 | 8.3 $\pm$ 2.5 | 0.040 $\pm$ 0.012 | 2.3 $\pm$ 0.2 |
| UGC 4499.....| 2.1         | 2.1                      | 1.0           | 16.1 $\pm$ 0.4 | 4.2 $\pm$ 1.0 | 0.018 $\pm$ 0.003 | 2.9 $\pm$ 0.2 |
| UGC 7603.....| 0.9         | 0.8                      | 1.0           | 16.8 $\pm$ 0.4 | 2.7 $\pm$ 0.5 | 0.021 $\pm$ 0.003 | 0.2 $\pm$ 0.2 |
| UGC 11861.....| 6.1         | 5.8                      | 1.0           | 13.3 $\pm$ 0.3 | 29.1 $\pm$ 6.3 | 0.010 $\pm$ 0.002 | 7.5 $\pm$ 0.7 |
| LSB F571-8...| 5.2         | 1.1                      | 1.4           | 12.9 $\pm$ 0.3 | 38.7 $\pm$ 6.8 | 0.024 $\pm$ 0.002 | 5.0 $\pm$ 0.2 |
| LSB F583-1....| 1.6         | 0.4                      | 1.4           | 15.1 $\pm$ 0.3 | 7.9 $\pm$ 2.1 | 0.013 $\pm$ 0.002 | 4.4 $\pm$ 0.2 |

* Stellar disk scale length; for UGC 4499 we also used $r_{1/4} = 0.3$ kpc as the scale radius of the stellar bulge.
2001) and $\Upsilon_* = 1.0$ for the late-type dwarf galaxies. This value was estimated using the model provided by Charlot & Longhetti (2001) with a star formation rate $SFR \propto e^{-t/\tau}$ ($t \approx 7$ Gyr and $\tau \approx 15$ Gyr; M. Longhetti 2001, private communication). Then we correct for the adiabatic contraction using the adiabatic invariant technique, and we derive the final rotation curve to be compared to the data.

In Figure 7 the analysis for the six galaxies of our sample is shown. In the left-hand panels the NFW is assumed as the representative mass distribution of the primordial halo (dotted lines), while in the right-hand panel of each galaxy a King model is adopted (dotted lines). The disk is represented by the dot-dashed lines and the final rotation curve, corrected for the halo adiabatic contraction, is the solid line. Asterisks are our high spatial resolution H\textalpha rotation curves combined in the outer parts with the H\textalpha data (squares).

It is clear that all the observed rotation curves are reproduced best when the dark matter in the primeval halo is distributed as a King profile. The NFW profile is always inconsistent with the inner parts of the observed rotation curves, as it predicts velocities that rise too fast.

4.2. Scaling Relations

Firmani et al. (2001) analyzed a sample of dark matter-dominated galaxies (dwarf and LSB) with accurate HI rotation curves taken from the literature. All these galaxies showed slowly rising rotation curves and evidence of soft cores. The authors correlated the halo scales from galaxies to galaxy clusters, including in the analysis the halo scales inferred from CL 0024+1654 and other clusters with a suspect evidence of flat mass distribution at the center. Surprisingly they found that the halo central density is independent of the halo mass, ranging from dwarf galaxies to galaxy clusters and the core radius scales with the mass. However, due to the low spatial resolution of the radio observations, the HI data are potentially affected by beam smearing, which could mask the real mass distribution in the halo inner regions.

With the optical rotation curves for dark matter-dominated galaxies, we correlate the halo scales from dwarf galaxies to galaxy clusters. Since the halos of these galaxies seem to be core-dominated and well-fitted by a King model with form parameter $f_p = 8$, we use the estimated values for the scales $\rho_0$ (central density) and $r_0$ (core radius) of the King profile derived in the previous section and corrected for halo adiabatic contraction in order to test the robustness of the scaling relations found by Firmani et al. (2001).

In Figure 8 the halo central density and the core radius are shown as functions of the maximum circular velocity for LSB and dwarf galaxies inferred by HI rotation curves taken from the literature (dark squares). The open circles are the optical high-resolution rotation curves by Swaters et al. (2000) but corrected for adiabatic contraction. Filled circles are our sample of high spatial resolution rotation curves. The two independent points on the right of the plot are the galaxy clusters: CL 0024+1654 and A1795.

The scale invariance (within a factor of 2) of the halo central density is preserved, and the core radius scales proportional to the halo mass. The optical rotation curves confirm the scale properties estimated in Firmani et al. (2001). Further observations are needed especially on galaxy cluster scales, for which there are still many uncertainties; furthermore, soft cores are not found at the center of every galaxy cluster (David et al. 2000) or they are very small (Arabadjis, Bautz, & Garmire 2001). Remarkably, if the core existence is confirmed on galaxy cluster scales the CDM models are unable to predict the scale invariance of the halo central density.

If future observations will confirm this scale invariance of the halo central density, it has interesting implications for the nature of the dark matter. If the dark matter is assumed to be warm, the maximum space phase density, defined as $f_{\text{max}} = \rho_0/\sigma^3$ with $\rho_0$ the halo central density and $\sigma$ the halo velocity dispersion ($\sigma \propto v_{\text{max}}$), has a finite value. As a consequence of Liouville’s theorem $f_{\text{max}}$ is preserved, implying an increase of the halo central density for more massive halos: $\rho_0 \propto v_{\text{max}}$ (Figure 8, dashed line in the top panel). This is inconsistent with the constant central density shown here. Indeed, if we accept the scale invariance of the halo central density on the halo mass ($\rho_0 \approx \text{const}$), this rules out the fermionic warm particles as candidates for the dark matter. On the other hand, if the dark matter is assumed to be weakly self-interacting, the scaling relations shown in this paper can be reproduced if the cross section is assumed to be inversely proportional to the halo dispersion velocity (D’Onghia, Firmani, & Chincarini 2002). However, the self-interacting dark matter suffers from other conflicts that make this scenario unlikely to solve all the problems of the CDM models (e.g., Gnedin & Ostriker 2001).

5. CONCLUSIONS

From the analysis of high spatial resolution rotation curves obtained with H\textalpha long slit spectroscopy of four late-type dwarf galaxies and two LSB galaxies we reach the following conclusions:

1. By comparing the H\textalpha and the HI rotation curves in the inner regions, we find a good agreement for all of the six galaxies except for LSB F571-8. In other words, the HI data available in the literature for these galaxies are not substantially affected by the modest spatial resolution of the radio observations. The galaxy F571-8 is seen edge-on so that different optical depth and projection effects may easily alter the observed rotation curve.

2. In the minimum disk hypothesis, in which we really neglect the disk contribution to the total gravitational potential, the observed rotation curves match better to the soft core density profile (Burkert) than to cuspy profiles (NFW and Moore). The profiles predicted by CDM N-body simulations are severely inconsistent in the inner regions, predicting rotation curves rising too fast within a few kpc.

3. By forcing the fit in the minimum disk hypothesis with the NFW profile, we were able to fit the observations reasonably well; however, the best fit has maximum velocities that are up to 30% higher than the velocity at the largest observed radius.

4. Accounting for the presence of baryonic matter in the nucleus, we find that the King profile (characterized by a soft density core) fits well to the primeval dark matter halo density profile derived from our rotation curves. This is not the case when the primeval dark matter halo density profile is modeled with an NFW profile. If a Moore profile is assumed for the initial halo, the discrepancy is exacerbated.

Finally, the optical rotation curves confirm for LSB and late-type dwarf galaxies halo central density close to the
Fig. 7.—Comparison between the observed rotation curves and the models in which the adiabatic contraction and the stellar disk component are taken into account. The left plots correspond to the models in which the primeval dark matter halo density profile is represented by an NFW model, while the right plots correspond to the models in which the primeval dark matter density profile is represented by a King model. Asterisks are the H\textalpha points, open squares are the H\texti points. The dot-dashed line is the contribution of the stellar disk, the dashed line is the primeval dark matter halo velocity profile, and the continuous line is the final rotation curve (after taking care of the adiabatic contraction) that must be compared to the observed rotation curve.
value of $0.05 \, h^2 \, M_\odot \, pc^{-3}$, as estimated previously on the basis of the H\textsc{i} data.

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Fig. 8.—Halo central density and the core radius shown as a function of the maximum circular velocity for LSB and dwarf galaxies inferred by H\textsc{i} rotation curves taken from the literature (filled squares); the open circles are the optical high-resolution rotation curves by Swaters et al. (2000) but corrected for adiabatic contraction. Filled circles are our sample of high spatial resolution rotation curves. The two independent points on the right of the plot are the galaxy clusters: CL 0024+1654 and A1795. The dashed line corresponds to the prediction in Sellwood (2000).