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MASS DENSITY PROFILES OF LOW SURFACE BRIGHTNESS GALAXIES

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ABSTRACT

We derive the mass density profiles of dark matter halos that are implied by high spatial resolution rotation curves of low surface brightness galaxies. We find that, at small radii, the mass density distribution is dominated by a nearly constant density core with a core radius of a few kiloparsecs. For $\rho(r) \sim r^{\alpha}$, the distribution of inner slopes α is strongly peaked around $\alpha = -0.2$. This is significantly shallower than the cuspy $\alpha \leq -1$ halos found in cold dark matter simulations. While the observed distribution of α does have a tail toward such extreme values, the derived value of α is found to depend on the spatial resolution of the rotation curves: $\alpha \approx -1$ is found only for the least well resolved galaxies. Even for these galaxies, our data are also consistent with constant-density cores ($\alpha = 0$) of modest (~1 kpc) core radius, which can give the illusion of steep cusps when insufficiently resolved. Consequently, there is no clear evidence for a cuspy halo in any of the low surface brightness galaxies observed.

Subject headings: dark matter — galaxies: fundamental parameters — galaxies: kinematics and dynamics

1. INTRODUCTION

Low surface brightness (LSB) galaxies are dark matter–dominated galaxies where the stellar populations make only a small contribution to the observed rotation curves. It is therefore straightforward to compare the observed rotation curves of these galaxies with those derived from numerical cosmological simulations, where the dark matter is the dominant component.

Early observation of dwarf and LSB galaxies showed that their rotation curves rose less steeply than predicted by numerical simulations based on the cold dark matter (CDM) hypothesis (Moore 1994; Flores & Primack 1994; de Blok & McGaugh 1997; McGaugh & de Blok 1998). In the CDM model, halos are characterized by a steep central cuspy power-law mass density distribution $\rho(r) \sim r^{\alpha}$. Initial simulations indicated that $\alpha = -1$ (Navarro, Frenk, & White 1996, hereafter NFW). More recent results indicate a more extreme value $\alpha = -1.5$ (e.g., Moore et al. 1998, 1999; Bullock et al. 1999). Rotation curves of dwarf and LSB galaxies, however, show a more solid-body–like rise consistent with a mass distribution dominated by a central constant-density core ($\alpha \simeq 0$) and hence are inconsistent with the CDM predictions. Similar conclusions have been reached by Salucci (2001) and Salucci & Borriello (2000) for high surface brightness disk galaxies.

The conclusions regarding LSB galaxies were based on H I observations with limited spatial resolution, and the data were in part affected by beam smearing. Even though McGaugh & de Blok (1998) showed that the steep signatures of the rotation curves implied by CDM could not be hidden by any reasonable amount of beam smearing, there were later suggestions that the observed data *were* consistent with the CDM predictions (van den Bosch et al. 2000; van den Bosch & Swaters 2000) if proper beam-smearing corrections were applied. Swaters, Madore, & Trewhella (2000) published optical rotation curves of five LSB galaxies from the de Blok, McGaugh, & van der Hulst (1996) sample and found that in several cases the inner rotation curve slopes were somewhat steeper than found from the H I curves. It is thus conceivable that the data could be reconciled with CDM models once beam-smearing corrections are properly taken into account. This is not borne out by improved data, as we show in this Letter.

2. THE DATA

McGaugh, Rubin, & de Blok (2001, hereafter MRdB), de Blok, McGaugh, & Rubin (2001, hereafter dBMR), and de Blok & Bosma (2001) present high-resolution hybrid Hα/H I rotation curves of LSB galaxies and show that a large fraction of them are characterized by a slow, solid-body–like rise. They compare (cuspy) CDM NFW halos and pseudoisothermal (core-dominated) halos (e.g., Begeman, Broeils, & Sanders 1991) with the data and find that the pseudoisothermal model is statistically a much better fit to the data. Most NFW model fits suffer from systematic effects resulting from the fitting program trying to reconcile $v(r) \sim r$ data with a steep $v(r) \sim r^{1/2}$ prediction. The discrepancies between H I and optical data are found to be less severe than initially suggested in Swaters et al. (2000): there is reasonable agreement between new optical data and the old H I curves in the majority of the cases (MRdB). The main conclusion drawn from the new data is that LSB galaxies cannot be well fitted by CDM rotation curves. Here we derive the mass density profiles that are required to give rise to the observed rotation curves. These can be compared directly with those predicted by theoretical models.

We use the sample of LSB and dwarf galaxy rotation curves described in dBMR, MRdB, and de Blok & Bosma (2001). This sample includes the five LSB galaxies originally presented

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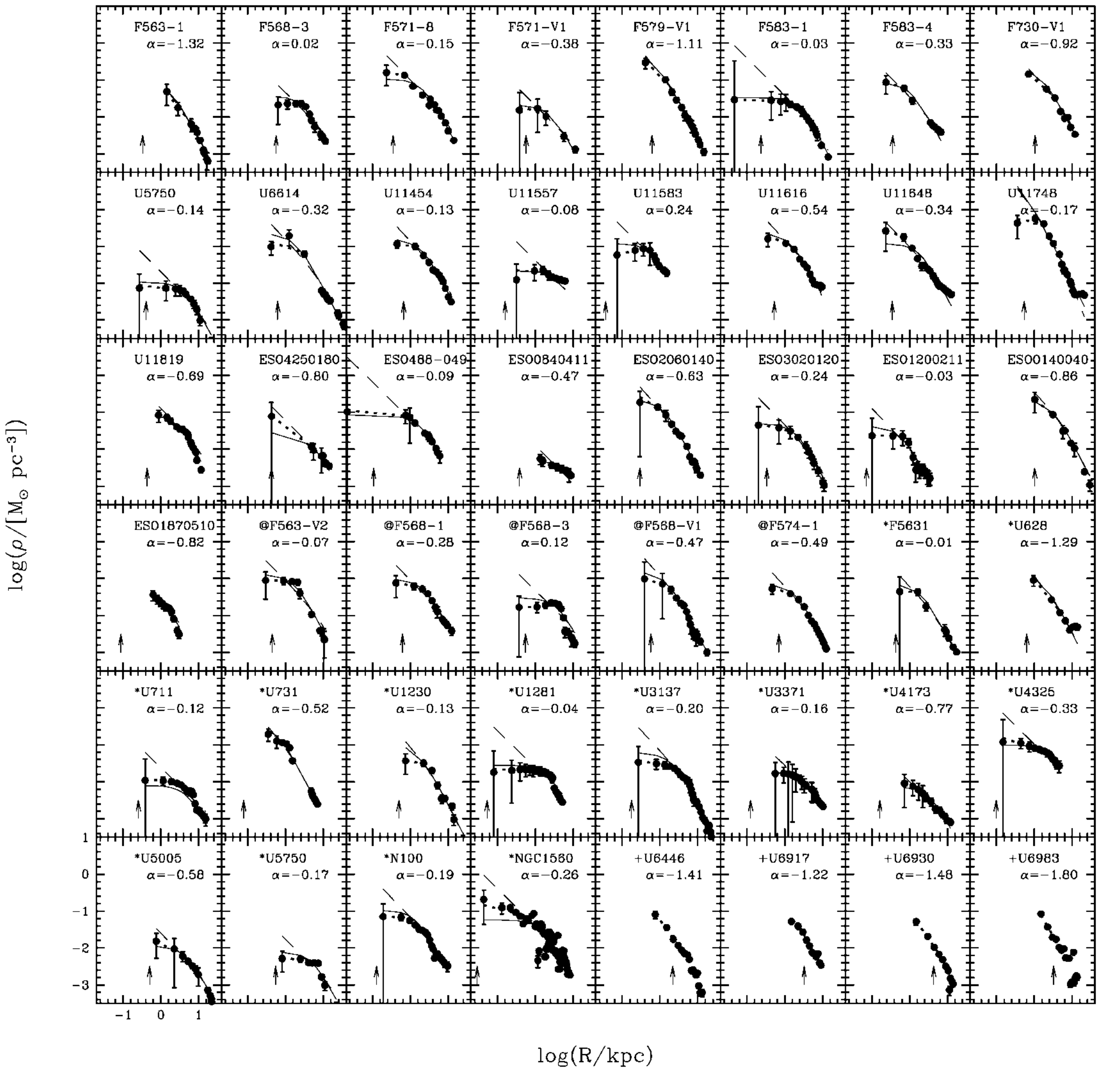

FIG. 1.—Mass profiles of LSB galaxies (*filled circles*) derived from high-resolution rotation curves. The profiles can be characterized by a steep r^{-2} outer component and a more shallow inner component ("core"). Also shown are the mass density profiles implied by the best-fitting minimum disk models from de Blok & Bosma (2001) and dBMR. Shown are the pseudoisothermal halo (*solid line*) and the NFW halo (*long-dashed line*). We have also fitted a power law to the inner shallow part (*thick short-dashed line*). The slope α is given in the top left corners of the panels. The arrows indicate the size of the seeing disk. All panels are at the same scale (denoted in bottom left corner). Galaxies are labeled with their names; those from de Blok & Bosma (2001) are furthermore labeled with an asterisk, those from Verheijen (1997) with a plus sign, and those derived from the Swaters et al. (2000) data with an "at" symbol.

in Swaters et al. (2000) that were rederived in dBMR. To this we have added the four LSB galaxies from the Ursa Major sample of Verheijen (1997) with $\mu_0(B) > 22.0$ mag arcsec^{-2} with reliable H I rotation curves.

3. RESULTS

In principle, one can invert an observed rotation curve to determine the parent mass distribution. In practice, this procedure can be unstable for thin disks (Binney & Tremaine 1987) (but see Sackett 1997). For LSB galaxies, the disk component is negligible since the potential is dominated by the dark matter halo. We therefore invert the observed rotation curves assuming a spherical mass distribution, which is a straightforward and robust procedure. From $\nabla^2\Phi = 4\pi G\rho$ and $\Phi = -GM/r$ one can derive the mass density $\rho(r)$:

$$4\pi G\rho(r) = 2\frac{v}{r}\frac{\partial v}{\partial r} + \left(\frac{v}{r}\right)^2, \qquad (1)$$

where v is the rotation velocity and r is the radius.

Implicit in these procedures are assumptions: that these galaxies are all dark matter dominated, that the gas motions are circular in a planar disk, and that the spectrum samples the nucleus and major axis. We also assume that the galaxies are symmetric. (The latter is a good assumption: MRdB, dBMR, and de Blok & Bosma 2001 omitted asymmetric galaxies from the samples, whereas the effects of any mild, residual asymmetries were incorporated in the error bars.)

Here we ignore mass contributions of the stellar and gas components. As long as these do not dominate the dynamics, as is the case in LSB galaxies, this "minimum disk" assumption is a good one. A minimum disk also produces an upper limit on the steepness of the halo profile as inclusion of gas and stars will tend to flatten the derived slopes. See also dBMR and de Blok & McGaugh (1997). In a forthcoming paper we show the results for nonminimum disk hypotheses, which are not substantially different from the ones derived here.

Figure 1 shows the derived mass density profiles. Over-

TABLE 1

Inner Power-Law Slope α

Galaxy	α	$\Delta\alpha$	$r_{\rm in}$ (kpc)	$V_{\rm sys}^{\rm hel}$ (km s^{-1})
de Blok et al. (2001)				
F563-1	−1.32	0.02	1.44	3502
F568-3	+0.02	0.19	0.64	5913
F571-8	−0.15	0.77	0.23	3768
F571-V1	−0.38	0.48	0.38	5721
F579-V1	−1.11	0.19	0.41	6305
F583-1	−0.03	0.19	0.05	2264
F583-4	−0.33	0.50	0.24	3617
F730-V1	−0.92	0.15	0.69	10714
UGC 5750	−0.14	0.14	0.81	4177
UGC 6614	−0.32	0.97	0.42	6377
UGC 11454	−0.13	0.38	0.44	6628
UGC 11557	−0.08	0.23	0.32	1390
UGC 11583	+0.24	0.11	0.07	128
UGC 11616	−0.54	0.44	0.35	5244
UGC 11648	−0.34	0.59	0.23	3350
UGC 11748	−0.17	0.73	0.35	5265
UGC 11819	−0.69	0.13	0.87	4261
ESO 0140040	−0.86	0.30	1.03	16064
ESO 0840411	−0.47	0.03	1.36	6200
ESO 1200211	−0.03	0.30	0.10	1314
ESO 1870510	−0.82	0.18	0.62	1389
ESO 2060140	−0.63	0.49	0.29	4704
ESO 3020120	−0.24	0.23	0.20	5311
ESO 4250180	−0.80	0.03	0.42	6637
ESO 488-049	−0.09	0.39	0.02	1800
de Blok & Bosma (2001)				
F563-1	−0.01	0.70	0.54	3502
UGC 628	−1.29	0.08	0.95	5451
UGC 711	−0.12	0.07	0.38	1984
UGC 731	−0.52	0.45	0.35	637
UGC 1230	−0.13	0.26	0.74	3837
UGC 1281	−0.04	0.01	0.08	157
UGC 3137	−0.20	0.10	0.27	982
UGC 3371	−0.16	0.10	0.56	819
UGC 4173	−0.77	0.13	0.73	861
UGC 4325	−0.33	0.03	0.15	523
UGC 5005	−0.58	0.09	0.76	3830
UGC 5750	−0.17	0.27	0.27	4177
NGC 100	−0.19	0.17	0.19	841
NGC 1560	−0.26	0.25	0.04	−36
Swaters et al. (2000)[a]				
F563-V2	−0.07	0.21	0.30	4312
F568-1	−0.28	0.16	0.41	6524
F568-3	+0.18	0.10	0.38	5913
F568-V1	−0.47	0.52	0.39	5768
F574-1	−0.49	0.26	0.47	6889
Verheijen (1997) UMa LSB Galaxies				
UGC 6446	−1.41	0.01	0.75	644
UGC 6917	−1.22	0.17	1.50	911
UGC 6930	−1.48	0.01	1.50	777
UGC 6983	−1.80	0.03	1.50	1082

[a] These values are based on our rederivation of the rotation curves using the method described in dBMR, based on the raw data as published in Swaters et al. 2000.

plotted are the profiles of the best-fitting pseudoisothermal and NFW halo as listed in dBMR and de Blok & Bosma (2001). The errors on the data points are derived by rigorously carrying through the errors in the rotation curve data points. The arrows indicate the size of the seeing disk for each galaxy. (For the four Verheijen 1997 galaxies we indicate the radio beam size.)

The shape of the mass density profiles can generally be characterized by two components: an outer one with an isothermal slope of −2 and a more shallow one in the inner parts. After determining the "break radius" where the slope changes most rapidly, we determine the slope of the inner component using a weighted least-squares fit. Table 1 collects the values of the inner slope. The range over which the power law is fitted is indicated by the range over which the fit is drawn in Figure 1. The uncertainty $\Delta\alpha$ is determined by remeasuring the slope twice, once by including the first data point outside the break radius and once by omitting the data point at the break radius. The maximum difference between these two values and the original slope is adopted as the uncertainty. The isothermal mass model generally follows the derived mass profile very well. The NFW models usually fail dramatically in the inner parts. For the galaxies, the signature of the shallow inner slope is usually already present well outside the seeing disk. Optical "beam smearing" can therefore not cause these shallow inner slopes.

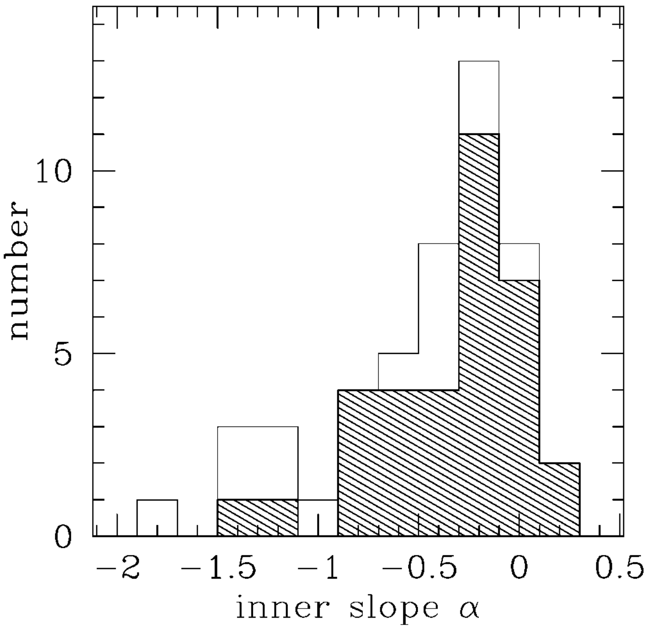

Fig. 2.—Histogram of the values of the inner power-law slope α of the mass density profiles presented in Fig. 1. We distinguish between well-resolved (*hatched histogram*) and unresolved (*blank histogram*) galaxies. The unresolved galaxies generally have higher values of α.

Minimum disk does provide relevant limits on the inner slopes as is particularly well illustrated by UGC 6614. This is a bulge-dominated giant LSB galaxy, and we expect the bulge to contribute significantly to the dynamics at small radius for any plausible stellar mass-to-light ratio. However, even in the minimum disk case, we find a shallow slope $\alpha = -0.3$. This means that for any nonminimum disk situation the dark matter must be depressed even further away from the NFW case (i.e., the true slope must be even flatter).

Values for the inner slopes (Fig. 2) are asymmetric. In Figure 2 we have distinguished between galaxies where the profile is well resolved and those where the turnover in the profile occurs at or within the seeing radius. The most unresolved galaxies tend to have the most negative values of α. The resolved galaxies define a well-determined peak at $\alpha = -0.2 \pm 0.2$ that is inconsistent with CDM predictions that $\alpha = -1.5$.

One possible point of concern is the wing of steeper slopes extending to $\alpha = -1.8$, where the extreme values originate from the Verheijen (1997) UMa LSB profiles. Does this mean that, despite all of the above, there are LSB galaxies that *can* be well fitted with CDM models? In addition, does the tendency

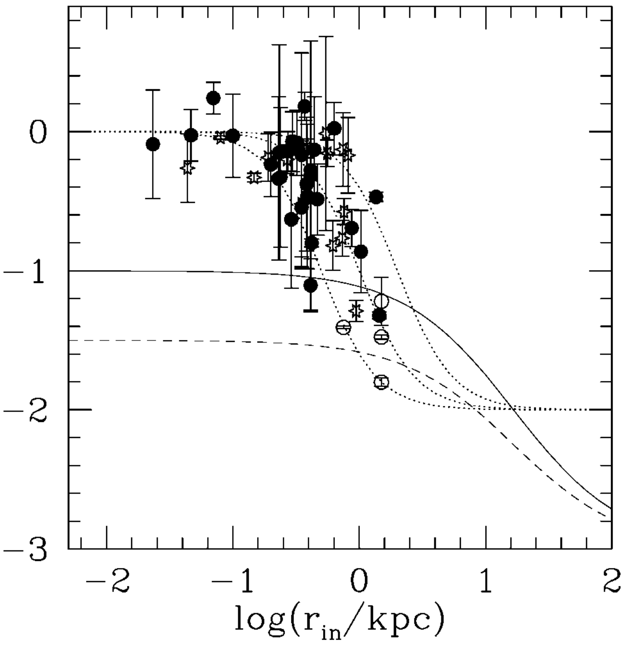

FIG. 3.—Value of the inner slope α of the mass density profiles plotted against the radius of the innermost point. Filled circles are from the dBMR sample; stars are from the de Blok & Bosma (2001) sample; open circles represent the four LSB galaxies from the Verheijen (1997) sample. Overplotted are the theoretical slopes of a pseudoisothermal halo model (*dotted lines*) with core radii of 0.5 (*leftmost*), 1 (*center*), and 2 (*rightmost*) kpc. The solid line represents an NFW model (NFW), the dashed line a CDM $r^{-1.5}$ model (Moore et al. 1999). Both of the latter models have parameters $c = 8$ and $V_{200} = 100$ km s^{-1}, which were chosen to fit approximately the data points in the lower part of the diagram.

of the UMa LSB galaxies to have steep slopes indicate systematic effects in the new LSB data? The answer to both questions is negative, as the following analysis shows.

Table 1 lists the radius in kiloparsecs, $r_{\rm in}$, of the innermost data point of each profile. For the LSB sample, generally $r_{\rm in} < 1$ kpc. For the UMa galaxies, we find larger $r_{\rm in}$: three of the four have $r_{\rm in} = 1.5$ kpc. In Figure 3, we plot the values of $r_{\rm in}$ versus the inner slope α. Also drawn are the logarithmic slopes as a function of radius for pseudoisothermal halos with core radii $R_C = 0.5$, 1, 2 kpc, as well as an NFW model and a CDM $r^{-1.5}$ model (Moore et al. 1999), both of the latter converging to a slope $\alpha = -3$ in the (far) outer parts. These two models are chosen to have parameters $c = 8$ and $V_{200} = 100$ km s^{-1} to match approximately the four UMa galaxies. However, this choice is not critical.

Galaxies with small values of $r_{\rm in}$ ($\lesssim$0.15 kpc) show clear evidence of a core ($\alpha \simeq 0$), whereas galaxies with larger values of $r_{\rm in}$ exhibit steeper slopes. Figure 3 shows that distribution is consistent with an isothermal halo with a core radius of a few kiloparsecs, whereas the NFW and CDM models do not match the data at all.

Hence, only galaxies with small values of $r_{\rm in}$ measure the core. Larger values sample a transition zone where the slope is changing from $\alpha = 0$ (center) to $\alpha = -2$ (outer isothermal regions). In the zone between ~1 and ~10 kpc the slopes of the pseudoisothermal and CDM models are approximately equal, so large values of $r_{\rm in}$ might erroneously lead to the conclusion that measured slopes are consistent with CDM. The four UMa galaxies (and some LSB galaxies) have $r_{\rm in}$ in this transition zone and thus show steep slopes. We have modeled the beam smearing or seeing effects potentially present in the optical data (discussed in a forthcoming paper) and find that we can strongly exclude the possibility that these affect the results down to resolutions of ~0″.1. We thus predict that higher spatial resolution data (with smaller values of $r_{\rm in}$) will also detect cores in the less well resolved galaxies.

Similar arguments apply to the beam-smearing–corrected H I curves in van den Bosch et al. 2000 and van den Bosch & Swaters (2000). With values $r_{\rm in} \sim 1$ kpc these data trace *not* the inner slope but instead the steep slope at the turnover of the constant-density core.

4. CONCLUSIONS

Mass density profiles of LSB galaxies exhibit inner slopes that are best described by a power law $\rho(r) \sim r^{\alpha}$ with $\alpha = -0.2 \pm 0.2$. This result implies that halos of LSB galaxies are dominated by cores. This result is inconsistent with the value $\alpha = -1.5$ predicted by CDM models. The steep slopes found for some LSB galaxies arise when the innermost data point is sampling the transition region between core and outer $\alpha = -2$ isothermal region, not the core itself. Our data are not consistent with CDM predictions but suggest that LSB galaxies have halos that contain cores of radii of order 1 kpc.

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