MASS DENSITY PROFILES OF LSB 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 kpc. For \( \rho(r) \sim r^\alpha \), the distribution of inner slopes \( \alpha \) is strongly peaked around \( \alpha = -0.2 \). This is significantly shallower than the cuspy \( \alpha \leq -1 \) halos found in CDM simulations. While the observed distribution of \( \alpha \) does have a tail towards such extreme values, the derived value of \( \alpha \) 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 (\( \sim 1 \) 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: galaxies: kinematics and dynamics — galaxies: fundamental parameters — dark matter

1. INTRODUCTION

Low Surface Brightness (LSB) galaxies are dark-matter dominated galaxies where the stellar populations only make 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 characterised 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). 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 (\( \alpha \approx 0 \)), 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 \( \text{H}1 \) 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 & Trehwella (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 \( \text{H}1 \) 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) (MRdB), de Blok,
McGaugh & Rubin (2001) (dBMR) and de Blok & Bosma (2001) present high-resolution hybrid Hα/Hi rotation curves of LSB galaxies, and show that a large fraction of them are characterised by a slow, solid-body-like rise. They compare (cuspy) CDM NFW halos (Navarro, Frenk & White 1996) and pseudo-isothermal (core-dominated) halos (e.g. Begeman, Broeils & Sanders 1991) with the data and find that the pseudo-isothermal 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 Hi and optical data are found to be less severe than initially suggested in Swaters, Madore & Trewella (2000): there is reasonable agreement between new optical data and the old Hi 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 to 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 in Swaters, Madore & Trewella (2000) that were re-derived in dBMR. To this we have added the 4 LSB galaxies from the Ursa Major sample of Verheijen (1997) with \( \mu_0(B) > 22.0 \) mag arcsec\(^{-2} \) with reliable Hi 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 \( \rho(r) \):

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

where \( v \) is the rotation velocity and \( r \) is the radius.

Implicit in this procedure 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 errorbars.)

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 non-minimum disk hypotheses, which are not substantially different from the ones derived here.

Figure 1 shows the derived mass density profiles. Over-plotted are the profiles of the best fitting pseudo-isothermal 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 4 Verheijen 1997 galaxies we indicate the radio beam size.)

The shape of the mass density profiles can generally be characterised 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 Fig. 1. The uncertainty \( \Delta \alpha \) is determined by re-measuring 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.

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 non-minimum 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 Fig. 2 we have distinguished between galaxies where the profile is well-resolved and those where the turn-over in the profile occurs at or within the seeing radius. The most unresolved galaxies tend to have the most negative values of \( \alpha \). 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? And does the tendency 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 kpc, \( r_{in} \), of the innermost data point of each profile. For the LSB sample generally \( r_{in} < 1 \kpc \). For the UMa galaxies we find larger \( r_{in} \): three of the four have \( r_{in} = 1.5 \kpc \). In Fig. 3, we plot the values of \( r_{in} \) versus the inner slope \( \alpha \). Also drawn are the logarithmic
slopes as a function of radius for pseudo-isothermal halos with core-radii \( R_C = 0.5, 1, 2 \) kpc, as well as a 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 approximately match the four UMa galaxies. However, this choice is not critical.

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

Hence, only galaxies with small values of \( r_{in} \) 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 \( \sim 1 \) and \( \sim 10 \) kpc the slopes of the pseudo-isothermal and CDM models are approximately equal, so large values of \( r_{in} \) might erroneously lead to the conclusion that measured slopes are consistent with CDM. The four UMa galaxies (and some LSB galaxies) have \( r_{in} \) in this transition zone and thus show steep slopes. We have modelled 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 \( \sim 0.1'' \). We thus predict that higher spatial resolution data (with smaller values of \( r_{in} \)) will also detect cores in the less well-resolved galaxies.

Similar arguments apply to the beam smearing corrected \( \text{H} I \) curves in van den Bosch et al. (1999) and van den Bosch & Swaters (2000). With values \( r_{in} \sim 1 \) 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 which contain cores of radii of order 1 kpc.

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## Table 1

**Inner power-law slope** \( \alpha \)

| Galaxy       | \( \alpha \) | \( \Delta \alpha \) | \( r_{\text{in}} \) (kpc) | \( V_{\text{sys}}^{\text{tot}} \) (km s\(^{-1}\)) |
|--------------|-------------|-----------------|-----------------|-----------------|
| de Blok, McGaugh & Rubin (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            |
| Swaters, Madore & Trewella (2000)* |             |                 |                 |                 |
| 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            |
| F574-V1      | -0.47       | 0.52            | 0.29            | 5768            |
| F574-1       | -0.49       | 0.26            | 0.47            | 6889            |
| Swaters, Madore & Trewella (2000)** |             |                 |                 |                 |
| Swaters, Madore & Trewella (2000)* |             |                 |                 |                 |
| 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            |

*These values are based on our re-derivation of the rotation curves using the method described in dBMR, based on the raw data as published in Swaters, Madore & Trewella (2000).
Fig. 1.— Mass profiles of LSB galaxies (filled circles) derived from high-resolution rotation curves. The profiles can be characterised 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 pseudo-isothermal halo (full line) and the NFW halo (long-dashed line). We have also fit a power-law to the inner shallow part (thick short-dashed line). The slope $\alpha$ 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 labelled with their name, those from de Blok & Bosma (2001) are furthermore labelled with a star, those from Verheijen (1997) with a plus-sign, and those derived from the Swaters, Madore & Trawhella (2000) data with an "@"-symbol.
Fig. 2.— Histogram of the values of the inner power-law slope $\alpha$ 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 $\alpha$.

Fig. 3.— Value of the inner slope $\alpha$ of the mass density profiles plotted against the radius of the innermost point. Black dots 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. Over-plotted are the theoretical slopes of a pseudo-isothermal halo model (dotted lines) with core radii of 0.5 (left-most), 1 (center) and 2 (right-most) kpc. The full line represents a NFW model (Navarro, Frenk & White 1996), 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 approximately fit the data points in the lower part of the diagram.