High resolution Rotation curves of Low Surface Brightness Galaxies

ABSTRACT

High resolution Hα rotation curves are presented for five low surface brightness galaxies. These Hα rotation curves do not confirm the rotation curves previously derived from H I observations (de Blok, McGaugh & van der Hulst 1996, MNRAS 283, 18), because the latter are affected by beam smearing, caused by the low resolution of the H I observations. We find that the rotation curves of low surface brightness galaxies have the same shapes as those of high surface brightness galaxies if scaled with optical disk scale lengths. Their rotation curves rise steeply in the inner parts and reach a flat part beyond about two disk scale lengths. Mass modeling shows that the contribution of the stellar component to the rotation curves may be scaled to explain most of the inner parts of the rotation curves, and that the dark halo only starts to dominate the gravitational potential outside the optical disk. On the other hand, well fitting mass models can also be obtained with lower contributions of the stellar disk. These observations suggest that the luminous mass density and the total mass density are coupled in the inner parts of these galaxies.

1 Introduction

The rotation curves of high surface brightness (HSB) spiral galaxies rise fairly steeply to reach an extended, approximately flat part, well within the optical disk (Bosma 1978, 1981a,b, Rubin, Ford & Thonnard 1978, 1980). The discovery that the rotation curves of these galaxies are more or less flat out to one or two Holmberg radii has been one of the key pieces of evidence for the existence of dark matter outside the optical disk (e.g., van Albada et al. 1985). Within the optical disk, the observed rotation curves can in most cases be explained by the stellar components alone (Kalnajs 1983, Kent 1986).

Low surface brightness (LSB) galaxies, which have only in recent years been discovered to exist in large numbers (e.g., Schombert & Bothun 1988, Schombert et al. 1992), are reported to have rotation curves shapes different from those of HSB galaxies. De Blok, McGaugh & van der Hulst (1996, hereafter BMH) were the first to study the properties of the rotation curves of these galaxies, and they concluded that rotation curves of LSB galaxies rise more slowly than those of HSB galaxies of the same luminosity and that they are often still rising at the outermost measured point. In a subsequent paper, de Blok & McGaugh (1997, hereafter BM) found that LSB galaxies were dominated by dark matter and that the contribution of the stellar disk to the rotation curve, even if scaled to its maximum possible value, could not explain the observed rotation curve in the inner parts. Unfortunately, most of their galaxies are only poorly resolved, often with only about two resolution elements along the major axis, making their observations sensitive to beam smearing.

The H I rotation curves of LSB galaxies have received a great deal of attention, because they provide additional constraints on theories of galaxy evolution and formation. An area of particular interest has been to compare the rotation curves of LSB galaxies with the density profiles of dark matter found from N-body simulations of cold dark matter (CDM) universes. McGaugh & de Blok (1998) argued that the rotation curves of LSB galaxies are difficult to reconcile with the shapes predicted from CDM simulations. On the other hand, Kravtsov et al. (1998) found the average halo profile of the LSB galaxies to be consistent with their simulations. Hernandez & Gilmore (1998) used the LSB galaxy rotation curves to constrain the initial conditions of galaxy formation, using several observational constraints, among which the rotation curves of LSB galaxies. They found a halo profile that is substantially different from that found in standard CDM models.

To investigate the rotation curve shapes in the inner parts
of LSB galaxies, we have obtained high resolution H$\alpha$ rotation curves for five LSB galaxies that have been previously studied in H I by BMH. The observations presented in this chapter do not confirm the H I rotation curves derived by BMH. Instead, we find rotation curves that rise more steeply than those derived from the H I observations.

The plan of this chapter is as follows. In Section 2 we describe the sample, observations and data reduction. In Section 3 we present the high resolution H$\alpha$ rotation curves and compare these to the H I curves presented in BMH. In Section 4 we present mass models, and in Section 5 the results presented here are compared to those of HSB galaxies.

2 Sample, observations and data reduction

The galaxies presented here were selected from the sample of LSB galaxies of BMH. Only galaxies were chosen that satisfied the criteria given in BM to define their best rotation curves. An overview of the properties of the galaxies is given in Table 1, which lists the name of the galaxy (1), the adopted distance in Mpc (2), the central surface brightness in mag arcsec$^{-2}$ (3), the disk scale length in kpc (4), the inclination angle (5), the position angle (6), the absolute magnitude (7) and the H I mass in units of $10^9 M_\odot$ (8).

The observations were carried out at the Palomar Observatory with the 200$''$ Hale telescope, on November 20 1998. The FWHM velocity resolution was 54 km s$^{-1}$, the pixel size in the spatial direction was 0.5$''$. All galaxies were observed in a single 1800s exposure. The slit was oriented along the major axis, at the position angle derived by BMH (see Table 1). Despite their low surface brightnesses, all galaxies showed up clearly on the TV screen. The slit could therefore accurately be aligned with the center of the galaxy by eye. The data were reduced using standard procedures in IRAF. The resulting H$\alpha$ position-velocity diagrams are presented in Fig. 1.

3 The high resolution rotation curves

To derive the rotation curves, we started by making Gaussian fits to the line profiles at each position along the major axis to obtain the radial velocities. These fits and their errors are overlayed on the H$\alpha$ position-velocity diagram in Fig. 1. The position of the galaxy centers were determined from the peak of the continuum light along the slit. All galaxies were sufficiently bright to allow us to determine the position of the center along the slit with an accuracy of less than 1$''$.

<table>
<thead>
<tr>
<th>Name</th>
<th>$D$</th>
<th>$\mu_0$</th>
<th>$h$</th>
<th>$i$</th>
<th>P.A.</th>
<th>$M_B$</th>
<th>H I mass</th>
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<tr>
<td>F563-V2</td>
<td>61</td>
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<td>5.3</td>
<td>26</td>
<td>13</td>
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<td>4.0</td>
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<tr>
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<td>77</td>
<td>23.1</td>
<td>4.0</td>
<td>40</td>
<td>169</td>
<td>-18.3</td>
<td>2.8</td>
</tr>
<tr>
<td>F568-V1</td>
<td>80</td>
<td>23.3</td>
<td>3.2</td>
<td>40</td>
<td>136</td>
<td>-17.9</td>
<td>2.5</td>
</tr>
<tr>
<td>F574-1</td>
<td>96</td>
<td>23.3</td>
<td>4.3</td>
<td>65</td>
<td>90</td>
<td>-18.4</td>
<td>3.5</td>
</tr>
</tbody>
</table>

$^a$ A P.A. of 90$''$ was used, derived from the optical image in BMH.

The systemic velocities, determined from the velocity at the position of the center, agree well with the H I systemic velocities.

To obtain a larger radial extent of the rotation curves, the H$\alpha$ data were combined with the H I data presented in BMH in the following way. The derived H$\alpha$ velocities were plotted on the H I position-velocity diagrams, derived from the data presented in BMH (see Fig. 2). The H$\alpha$ velocities were found to agree well with the H I data if beam smearing effects are taken into account. As discussed in Chapter 4, the distribution of H I is an important parameter in determining the magnitude of beam smearing. Unfortunately, BM have not taken this into account and therefore underestimated the effect of beam smearing.

Because the H I and the H$\alpha$ data agree well, we have used the H I data to determine rotation velocities outside radii where we found H$\alpha$ emission. Note that the H I extends only little beyond the H$\alpha$. Next, the rotation curves derived for the approaching and the receding sides were combined. The H$\alpha$ points were sampled every 2$''$, the H I points every 7.5$''$. The errors on the rotation velocities were estimated

![Figure 1: H$\alpha$ position-velocity diagrams for the five LSB galaxies, binned to 1$''$. Contour levels are at -2, 2, 4, 8, 16, 24, 32 times the r.m.s. noise. The dots with errorbars give the derived radial velocities with the formal errors from Gauss fits to the velocity profiles. The solid lines represent the rotation curves, derived as described in section 3.1. The vertical dotted line indicates the galaxy center, the horizontal dotted lines the heliocentric systemic velocities.](image-url)
Chapter 8. High resolution rotation curves of low surface brightness galaxies

Figure 2: The Hα radial velocities (dots with error bars) and the high resolution rotation curves (thick solid lines) overlayed on the H I data from de Blok, McGaugh & van der Hulst (1996). The H I contour levels are -3, -1.5, 1.5, 3, 4.5, ... times the r.m.s. noise. Negative contours are dotted. For increased signal-to-noise ratios, the H I position velocity diagrams have been obtained from Hanning smoothed data.

from the differences between the two sides and the uncertainties in the derived velocities. We will refer to these rotation curves as the high resolution rotation curves (HRC).

The derived HRCs are shown in Fig. 3 together with the H I rotation curves presented in BH. Note that due to the neglect of beam smearing the H I rotation curves systematically underestimate the inner slopes of the rotation curves, especially for F568-V1 and F574-1. Both these galaxies have a central depression in the H I distribution, as can be seen in the H I maps presented in BMH. The spatial smearing of H I from larger radii into the observed central depression leads to an apparent solid body-like rotation curve, in particular for the highly inclined galaxy F574-1.

4 Mass modeling

For the mass modeling presented here we have used the same parameters for the thickness of the gaseous and stellar disks as BM have done. The stellar disk was assumed to have a vertical sech-squared distribution, with a scale height $z_0 = h/6$. R-band light profiles, presented in de Blok, van der Hulst & Bothun (1995) and BMH, were used to calculate the contribution of the stellar disk to the rotation curve. The H I was assumed to reside in an infinitely thin disk. The only difference with the mass models presented in BM is that we have decomposed the light profile of F568-1 in a disk and a central component, and fitted these components to the rotation curve separately. In the other galaxies no significant central components are present.

For the dark matter component we have used an isothermal halo, which has a rotation curve that is well approximated by

$$v_{\text{halo}}^2(r) = 4\pi G \rho_0 r_c^2 \left[ 1 - \frac{r_c}{r} \arctan \left( \frac{r}{r_c} \right) \right],$$

where $r_c$ is the halo core radius and $\rho_0$ is the central density.

One of the major uncertainties in fitting a mass models to rotation curves, in absence of an independent measurement of the stellar mass-to-light ratio $\Upsilon_*$, is the uncertainty in the contribution of the stellar disk to the rotation curve. However, limits on $\Upsilon_*$, and hence on the dark matter content, can be obtained by assuming that the contribution of the stellar disk to the rotation curve is either maximal or minimal.

In the maximum disk mass models, the contribution of the stellar disk to the rotation curve is scaled to explain most of the inner parts of the rotation curve. The resulting rotation curve fits are shown in Fig. 4. What immediately strikes the eye is that, in contrast with the findings of BM, the inner parts of the rotation curves can be explained almost entirely by the contribution of the stellar disk in all of these LSB galaxies, except for F568-3. This galaxy has a strong bar,
Figure 4: Mass models fitted to the high resolution rotation curves. The top panels give maximum disk fits, the bottom panels give fits with a stellar mass-to-light ratio of zero. The dotted line represents the contribution of the stellar disk to the rotation curve, the dashed line the contribution of the gas, the long-dashed line represents the dark halo, and the full line represented the total model rotation curve. For F568-1, the dot-dashed line represents the contribution of the central component to the rotation curve.

Table 2: Mass model parameters

<table>
<thead>
<tr>
<th>Name</th>
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</thead>
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<td></td>
<td>$\Upsilon_c$</td>
<td>$r_c$</td>
</tr>
<tr>
<td>F563-V2a</td>
<td>5.4</td>
<td>0.67</td>
</tr>
<tr>
<td>F568-1b</td>
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<td>–</td>
</tr>
<tr>
<td>F568-3</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>F568-V1</td>
<td>9.3</td>
<td>6.7</td>
</tr>
<tr>
<td>F574-1</td>
<td>3.7</td>
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</tr>
</tbody>
</table>

| a For this galaxy no $R$-band data are available, mass modeling has been done with $B$-band data. b F568-1 has a central light component with $\Upsilon_c = 14.4$, for the maximum disk fit.

which may affect the derived rotation curve.

The required stellar mass-to-light ratios for the maximum disk fits (listed in Table 2), may be high, up to 17 in the $R$-band. Most of these mass-to-light ratios are well outside the range of what current population synthesis models predict (e.g., Worthey 1994). On the other hand, the stellar content and the processes of star formation in LSB galaxies may be different from those in HSB galaxies.

For these maximum disk fits the dark halo parameters (see Table 2) are ill defined for most galaxies in our sample, because most of the HRCs do not extend to large radii. Nonetheless, it is clear that in these maximum disk fits the contribution of the dark halo will only become important outside the optical disk.

The other extreme for the contribution of stellar disk to the rotation curve is to assume that its contribution is negligible. From Fig. 4 it is clear that these mass models fit the rotation curves equally well as the maximum disk models. In fact, any mass-to-light ratio lower than the maximum disk mass-to-light ratio provides a good fit. The dark halo parameters for the minimum disk fit are listed in Table 2. High central densities of dark matter and small core radii are required to explain the observed steep rise in the HRCs.

Irrespective of the contribution of the stellar disk to the rotation curve, the similarity between the shapes of the observed rotation curves and those of the stellar disks suggests that the total mass density and the luminous mass density are coupled over the region of the optical disk.

5 Comparison to HSB galaxies

The HRCs we derived for the LSB galaxies rise steeply in the inner parts, and reach a flat part beyond about two disk scale lengths, similar to what is found for the rotation curves of HSB galaxies. In Fig. 5, we compare the rotation curves for LSB galaxies (dotted lines) with those of three typical late-type HSB galaxies from Begeman (1987), represented by the full lines. These are: NGC 2403, NGC 3198 and NGC 6503. All the galaxies in Fig. 5 have no or only weak bulges. In the top panel of Fig. 5 the radii are given in kpc. In these units, the rotation curves of LSB galaxies rise more slowly than those of HSB galaxies, indicating that these galaxies not only have lower surface brightnesses, but also lower total mass densities, as was also found by de Blok & McGaugh (1996).

In the bottom panel of Fig. 5 the rotation curves are scaled by optical disk scale length and normalized to the velocity at two disk scale lengths for ease of comparison (this probably does not introduce systematic effects because the maximum difference in absolute magnitude between the galaxies in Fig. 5 is only 1.5 mag). Compared in this way, the rotation curves of LSB and HSB galaxies have similar shapes, consistent with the concept of a ‘universal rotation curve’ (Persic, Salucci & Stel 1996, see also Rubin et al 1985). The HSB galaxies shown here have surface brightnesses that are on average 2 mag arcsec$^{-2}$ brighter than those
of the LSB galaxies. This strongly suggests that the rotation curve shape is independent of surface brightness.

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