

TESTING MODIFIED NEWTONIAN DYNAMICS WITH LOW SURFACE BRIGHTNESS GALAXIES: ROTATION CURVE FITS

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ABSTRACT

We present modified Newtonian dynamics (MOND) fits to 15 rotation curves of low surface brightness (LSB) galaxies. Good fits are readily found, although for a few galaxies minor adjustments to the inclination are needed. Reasonable values for the stellar mass-to-light ratios are found, as well as an approximately constant value for the total (gas and stars) mass-to-light ratio. We show that the LSB galaxies investigated here lie on the one, unique Tully-Fisher relation, as predicted by MOND. The scatter on the Tully-Fisher relation can be completely explained by the observed scatter in the total mass-to-light ratio. We address the question of whether MOND can fit any arbitrary rotation curve by constructing a plausible fake model galaxy. While MOND is unable to fit this hypothetical galaxy, a normal dark-halo fit is readily found, showing that dark matter fits are much less selective in producing fits. The good fits to rotation curves of LSB galaxies support MOND, especially because these are galaxies with large mass discrepancies deep in the MOND regime.

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

1. INTRODUCTION

The inability of the visible mass components in disk galaxies to account for the observed rotation curves is usually interpreted as evidence for the existence of an additional, invisible mass component. Other theories suggest that this mass discrepancy is an indication of a breakdown of classical Newtonian dynamics. It is difficult to evaluate these theories, because only a few make specific and testable predictions.

One of the exceptions is the modified Newtonian dynamics (MOND), advocated by Milgrom (1983, 1989) and Sanders (1990, 1996). This theory postulates that Newton's law of gravity should be modified for very small accelerations, with the result that any need for dark matter disappears. Fits to rotation curves of high surface brightness (HSB) galaxies using MOND are of equal quality as the fits made using a dark matter halo (see Sanders 1996). MOND is, however, also able to satisfactorily explain observations of the dynamics of, for example, dwarf galaxies and dwarf spheroidals (see the discussion in Milgrom 1995; also McGaugh & de Blok 1998b, hereafter Paper II).

For a complete description of MOND, its predictions, and observational results, we refer to Milgrom (1983, 1989), Sanders (1990), Begeman, Broeils, & Sanders (1991), Bekenstein & Milgrom (1984), and Sanders (1996). An extensive description of MOND results in the context of low surface brightness (LSB) galaxies is given in Paper II.

MOND assumes that the force law changes from the conventional Newtonian form when the acceleration of a

test particle is much smaller than a limiting acceleration a_0 , where a_0 is a universal constant. Thus, while the normal Newtonian acceleration $g_N = GM/r^2$, which a mass M exerts on a test particle at distance r is identical to the true test-particle acceleration g for accelerations $g \gg a_0$, in the MOND limit (i.e., $g \ll a_0$) the implied Newtonian acceleration is related to the true test-particle acceleration g by $g_N = g^2/a_0$.

The acceleration a_0 is a fundamental parameter in the MOND theory. From rotation curve fitting to high-quality rotation curves, Begeman et al. (1991) determined a value of $1.2 \times 10^{-10} \text{ m s}^{-2}$ (for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which we adopt throughout this paper).

As described in Paper II, LSB galaxies provide a strong test of MOND. Their low surface densities imply accelerations $g < a_0$, which means that these galaxies should be almost completely in the MOND regime. Milgrom (1983, 1989) made a number of testable predictions on the shapes of rotation curves and noted that low surface density galaxies should have slowly rising rotation curves. This expectation of MOND is confirmed by the observed rotation curves. In Newtonian terms this translates to these galaxies having large mass discrepancies (McGaugh & de Blok 1998a, hereafter Paper I).

This brings us to one of the more pronounced differences between MOND and classical Newtonian dynamics, which is the explanation of the Tully-Fisher (TF) relation. As is described in detail in Paper I (see also Zwaan et al. 1995), the fact that LSB galaxies are observed to obey the same TF relation as HSB galaxies implies a strong coupling between the central surface brightnesses of the disks of galaxies and their total mass-to-light ratios (which include dark matter). Assuming standard Newtonian dynamics, this implies that LSB galaxies have a higher total mass (within the disk radius) than HSB galaxies of the same asymptotic velocity.

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It is hard to derive this result in the standard context without a lot of fine-tuning.

MOND predicts that all galaxies should fall on one mass-velocity relation, which takes the form $V_\infty^4 = M G a_0$, where V_∞ is the asymptotic velocity and M is the total mass of the galaxy (that is, the mass of stars and gas). Once the value of a_0 is fixed, this relation becomes absolute and can be tested and falsified.

We use the rotation curves of 15 LSB galaxies to do a MOND analysis. The fitting procedure is described in § 2; § 3 presents the results. In § 4 we discuss whether MOND can fit any rotation curve, and we present our conclusions in § 5.

2. FITTING LSB ROTATION CURVES WITH MOND

In this paper we fit the rotation curves of the sample of 15 LSB galaxies presented in van der Hulst et al. (1993), de Blok, McGaugh, & van der Hulst (1996), and de Blok & McGaugh (1997) using the MOND prescription. We refer to these papers for a description of the properties of LSB galaxies and their rotation curves.

The rotation curves were fitted following the procedure outlined in Begeman et al. (1991) and Sanders (1996). To be consistent with the results presented in Sanders (1996), we have assumed that the stars and the gas are both in an infinitesimally thin disk (for our purposes this assumption has no appreciable impact on the stellar rotation curve; see Broeils 1992). The Newtonian rotation curves of the visible components (stars and H I) were determined first. The rotation curve of the stars was computed assuming that the mass-to-light ratio of the stars $(M/L)_*$ is constant with radius. The rotation curve of the gas was computed using the radial H I surface density profile, after multiplying this by 1.4 to take the contribution of He into account. We ignore any molecular gas: observations suggest that LSB galaxies contain only small amounts of molecular gas (Schombert et al. 1990; Knezek 1993; de Blok & van der Hulst 1998). With the Newtonian accelerations known, the MOND acceleration can be computed (see Paper II) and the observed rotation curves fitted using a least-squares program.

The fitting procedure has three free parameters: the distance D to the galaxy, the mass-to-light ratio of the stellar disk $(M/L)_*$, and the value of the constant a_0 . Because a_0 is supposed to be a universal constant, we fix it at the value determined in Begeman et al. (1991). Since the LSB galaxies investigated here are sufficiently far away that the redshift is a fair indicator of the distance, we take the distance D to be fixed at the values given in de Blok et al. (1996), assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This leaves $(M/L)_*$ as the *only* free parameter. For very gas rich galaxies, there are effectively no free parameters, because the dynamics are completely dominated by the gas component, and the contribution of the stars can be ignored for any reasonable value of $(M/L)_*$.

2.1. Results

The rotation curves and MOND fits are presented in Figure 1 and Table 1. Of the sample presented in de Blok & McGaugh (1997), we have not used F571–8 and F571–V2. F571–8 is an edge-on galaxy, and since the fits depend crucially on the photometric profile, the simple analysis done in de Blok et al. (1996) does not suffice here (because of uncertainties in the extinction; see Barnaby & Thronson 1994). For F571–V2 no photometry is available. The results presented in Table 1 differ slightly from those presented in Paper II. This is because we now fit the entire shape of the rotation curve rather than just the asymptotic velocity.

As can be seen in Figure 1, a good fit to the rotation curve was readily found for the majority of the galaxies. These fits are shown in the two leftmost columns in Figure 1. The ease with which these one-parameter fits were obtained is remarkable, especially if one keeps in mind that in LSB galaxies the dynamics are often dominated by the gas rather than the stars. This severely limits the possible values for $(M/L)_*$ and the freedom with which the MOND recipe has to produce a good fit.

For six galaxies a good fit did not occur trivially. The corresponding “bad” fits are shown in the third column in Figure 1. Were we to stop here, we would have to claim to have falsified MOND in spite of many good fits and confirmed predictions. It is therefore necessary to examine the uncertainties in the data before making such a radical step.

TABLE 1
RESULTS OF MOND FITS

| Name | V_{\max} | L_B | μ_B | D | M_{gas} | $(M/L_B)_*$ | $(M/L_R)_*$ | (M_{tot}/L_B) | i [i_{MOND}] |
|--------------|------------|-------|---------|-----|------------------|-------------|-------------|------------------------|---------------------------|
| F563–1..... | 111 | 0.135 | 23.6 | 45 | 0.385 | 2.97 | 3.99 | 5.82 | 25 |
| F563–V2..... | 111 | 0.302 | 22.1 | 61 | 0.321 | 1.81 | (2.38) | 2.87 | 29 |
| F565–V2..... | 51 | 0.023 | 24.7 | 48 | 0.084 | 2.18 | 2.70 | 5.85 | 60 [31] |
| F568–1..... | 119 | 0.275 | 23.8 | 85 | 0.557 | 3.01 | 3.96 | 5.03 | 26 |
| F568–3..... | 120 | 0.331 | 23.1 | 77 | 0.394 | 1.33 | 1.62 | 2.52 | 40 |
| F568–V1..... | 124 | 0.224 | 23.3 | 80 | 0.343 | 2.96 | 3.80 | 4.49 | 40 |
| F571–V1..... | 73 | 0.102 | 24.0 | 79 | 0.164 | 0.66 | 0.84 | 2.26 | 35 [30] |
| F574–1..... | 100 | 0.372 | 23.3 | 96 | 0.485 | (0.54) | 0.71 | 1.85 | 65 |
| F583–1..... | 85 | 0.063 | 24.1 | 32 | 0.243 | 1.68 | 1.96 | 5.53 | 63 |
| F583–4..... | 67 | 0.093 | 23.8 | 49 | 0.077 | (0.24) | 0.31 | 1.07 | 55 |
| U128..... | 131 | 0.513 | 23.2 | 60 | 0.882 | 0.84 | 1.06 | 2.56 | 55 |
| U1230..... | 102 | 0.324 | 23.3 | 51 | 0.812 | 1.16 | 1.71 | 3.67 | 22 [17] |
| U5005..... | 99 | 0.204 | 23.8 | 52 | 0.406 | (3.65) | 4.80 | 5.64 | 41 [30] |
| U5750..... | 75 | 0.468 | 23.5 | 56 | 0.140 | (0.68) | 0.89 | 0.98 | 64 [39] |
| U5999..... | 155 | 0.170 | 23.5 | 45 | 0.252 | (0.53) | 0.70 | 2.01 | 14 [22] |

NOTE.—Units: V_{\max} is in km s^{-1} , L_B in $10^{10} L_\odot$, M_{gas} in $10^{10} M_\odot$, μ_B in mag arcsec^{-2} , D in Mpc, and (M/L) in M_\odot/L_\odot in the respective passbands; i is in degrees. Values between brackets are B -band values that were converted from R -band observations or vice versa. Inclination values between square brackets are values demanded by MOND to produce good fits.

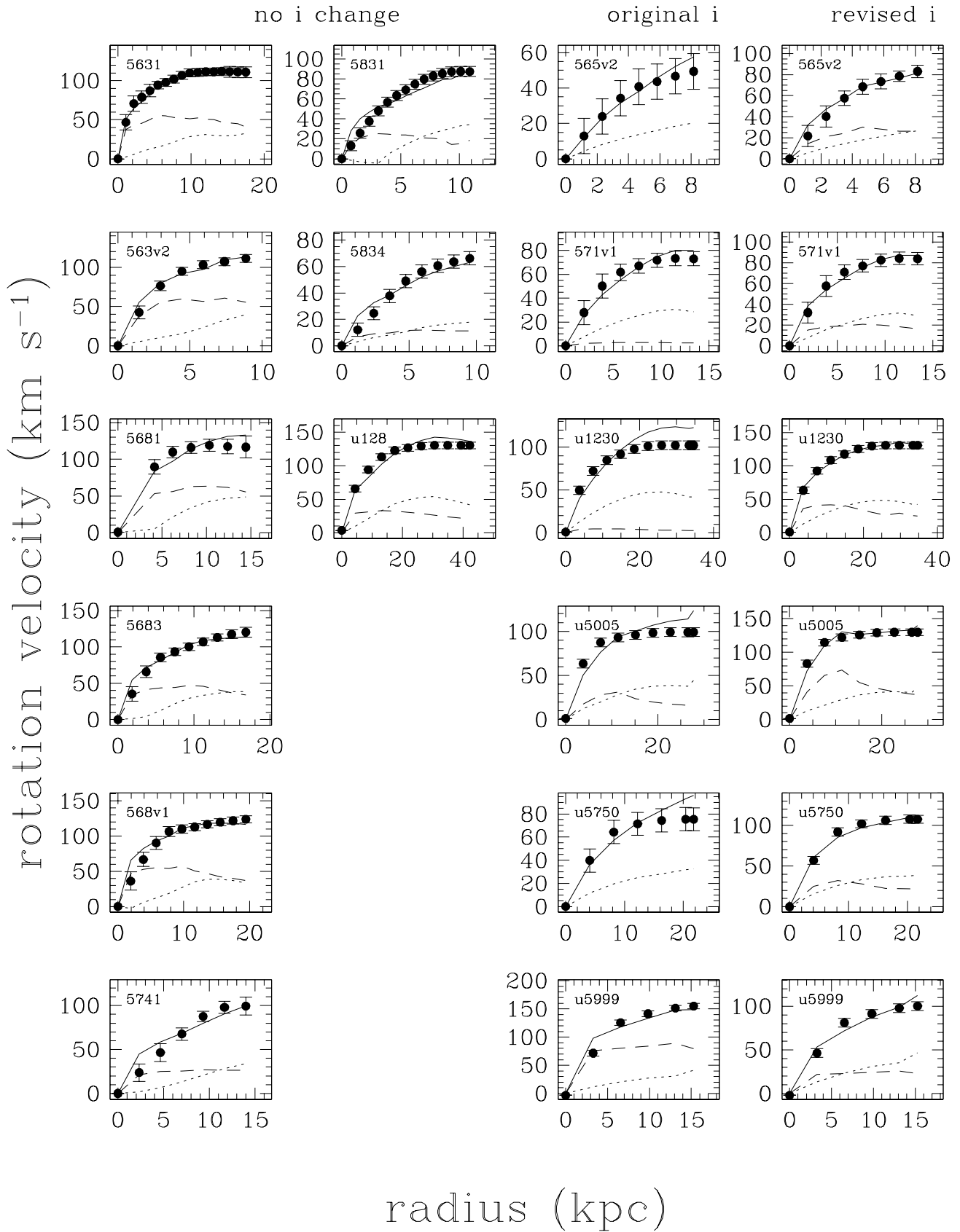


FIG. 1.—MOND fits to the rotation curves of LSB galaxies. The two leftmost columns show those fits where the inclination was not adjusted. The third column shows the “bad” fits where the inclination was not adjusted. The fourth and rightmost column shows the same six galaxies, but with inclinations changed to produce a good MOND fit. The dotted line shows the Newtonian rotation curve of the stellar disk, scaled with the appropriate $(M/L)_*$ value. The dashed line shows the Newtonian rotation curve of the gas. The solid line shows the resulting curve derived using the MOND recipe. The solid circles are the observed curves.

For each galaxy there are two parameters that might affect our ability to obtain a fit. One is the distance to the galaxy D , and the second is the inclination of the galaxy i (a_0 is supposed to be a universal parameter, and varying it from galaxy to galaxy would be against the spirit of MOND).

2.1.1. Distance Uncertainties

We have made two-parameter fits to the six “bad” curves with $(M/L)_*$ and D free. The results are shown in Table 2. Except for UGC 5999, we find that a two-parameter fit prefers smaller distances that are typically $\sim 60\%$ of the original distance. Because the galaxies are not near Virgo and have a sufficiently large redshift that this is a fair indicator of the distance, we think it is unlikely that these fits show a realistic picture.

A closer study of the fits shows that the distance factor is almost entirely caused by the fit overestimating the rotation velocity in the outer parts (see the third column in Fig. 1). This is caused by the gas-rotation curve having relatively high velocities in the outer parts. In order to accommodate the rotation curve of the stellar disk, the fitting procedure tries to reduce the amplitude of the gas-rotation curve by reducing the gas mass; i.e., it brings the galaxy in closer.

With D free, reasonable values of $(M/L)_*$ between 0.5 and 3 are obtained. However, one should keep in mind that the amplitude of the gas-rotation curve in the outer parts essentially forces us to adopt a particular value of D and, consequently, also forces us to adopt a value of $(M/L)_*$. Therefore, we cannot use D to improve the fits.

2.1.2. Inclination Uncertainties

The inclinations of LSB galaxies are difficult to constrain from the shapes of their outer isophotes (McGaugh & Bothun 1994; de Blok, van der Hulst, & Bothun 1995; de Blok et al. 1996). Yet this is essentially the only information we have that is independent of the kinematics.

The total rotation curve and the rotation curves of the stars and the gas each depend differently on the inclination. The total rotation velocity can be derived from the observed rotation velocity by $V_{\text{tot}} = V_{\text{obs}}/\sin i$. The rotation velocity of the gas and stars needs to be derived from the true surface density, which in turn is determined from the observed surface density σ_{obs} , so that $V_{\text{gas,stars}} \sim \sigma_{\text{obs}} \cos i$. The different dependencies on i will change the ratios between the total rotation curve and the stellar and gas rotation curves. Changes of only a few degrees can have quite noticeable effects for relatively face-on galaxies.

If the inclination is underestimated, the inclination-corrected observed velocities are too high. The gas contribution, which dominates in the outer parts, has no scaling factor built in and is therefore unable to fit these velocities. This can be compensated for by using a larger value of

$(M/L)_*$, but this will result in a model rotation curve with the wrong shape, because it will overestimate the velocity in the inner parts by a large factor.

The effects of overestimating the inclination are the reverse. The inclination-corrected observed velocities are too low, so that the rotation curve of the gas alone suffices to fit the data in the outer parts. Consequently, only a very modest or even zero or negative value of $(M/L)_*$ is needed. This again results in a model curve with the wrong shape: velocities too low in the inner parts and too high in the outer parts. There is only a narrow range in inclination where both the inner and outer parts are fitted equally well.

In deriving the best value for the inclination, we first changed the inclinations in a systematic way starting from the initial value from de Blok et al. (1996) and rederived the mass models for each value of the inclination. We used the χ^2 value to select a range of inclinations that yielded good fits. This range was then narrowed by inspecting these fits by eye and choosing those fits that most closely mimicked the behavior of the high-resolution fits presented in Sanders (1996). This means that the Newtonian rotation curve of the stellar disk should be able to describe the innermost one-third of the rising part of the observed rotation curve. In practice, the values for the inclination that were determined in that way are constrained to typically within 4° .

We now discuss on a case-by-case basis the validity of changing the inclination in these six galaxies. The rightmost two columns in Figure 1 show the original and revised fits of these two galaxies. Figure 2 shows slightly smoothed optical R -band pictures of the six galaxies with ellipses superimposed whose axis ratios correspond to the original assumed inclination and the derived MOND inclination. The MOND inclination values are also given in Table 1.

F565 – V2: At the original inclination of 60° , no fit with $(M/L)_* > 0$ could be made. The inclination needs to be changed to 44° before positive $(M/L)_*$ values are produced by the fitting procedure. The best fitting MOND value is 31° . This might mean that we are missing a face-on LSB disk underlying the elongated structure we now observe as the galaxy. Finding such an LSB disk will be made difficult by the presence of a bright star just outside the region shown (see Fig. 2 in de Blok et al. 1996).

F571 – V1: The inclination had to be changed from 35° to 30° , which is still fully consistent with the optical picture (Fig. 2).

UGC 1230: Only a very minor change was needed. The original value derived in van der Hulst et al. (1993) is 22° . MOND needs a value of 17° in order to produce a good fit. Note that the quality of the fit for this face-on system depends critically on the inclination. Using MOND to fit the rotation curve of a face-on galaxy could actually tie down its inclination to within a few degrees. This is impossible with a classical dark halo fit.

UGC 5005: The original value for the inclination of this galaxy is 41° . MOND demands an inclination in the range 26° to 30° for the best fits. Here we adopt a value of 30° . Figure 2 shows that this value is still consistent with the observed axis ratio.

UGC 5750: Good solutions are only found for inclinations between 38° and 42° . The value of 64° from van der Hulst et al. (1993) is ruled out. The new low value can only be consistent with the optical axis ratio if there is an LSB face-on disk underlying the observed barlike structure. This

TABLE 2
RESULTS OF MOND FITS WITH DISTANCE FREE

| Galaxy | D | D_{MOND}/D | $M/L_{*,df}$ |
|----------------|-----|---------------------|-----------------|
| F565 – V2..... | 48 | 0.60 ± 0.07 | 0.33 ± 0.15 |
| F571 – V1..... | 79 | 0.65 ± 0.11 | 0.79 ± 0.25 |
| U1230..... | 51 | 0.63 ± 0.03 | 0.58 ± 0.07 |
| U5005..... | 52 | 0.53 ± 0.03 | 2.04 ± 0.09 |
| U5750..... | 56 | 0.45 ± 0.55 | 0.43 ± 0.13 |
| U5999..... | 45 | 2.82 ± 0.39 | 3.61 ± 1.65 |

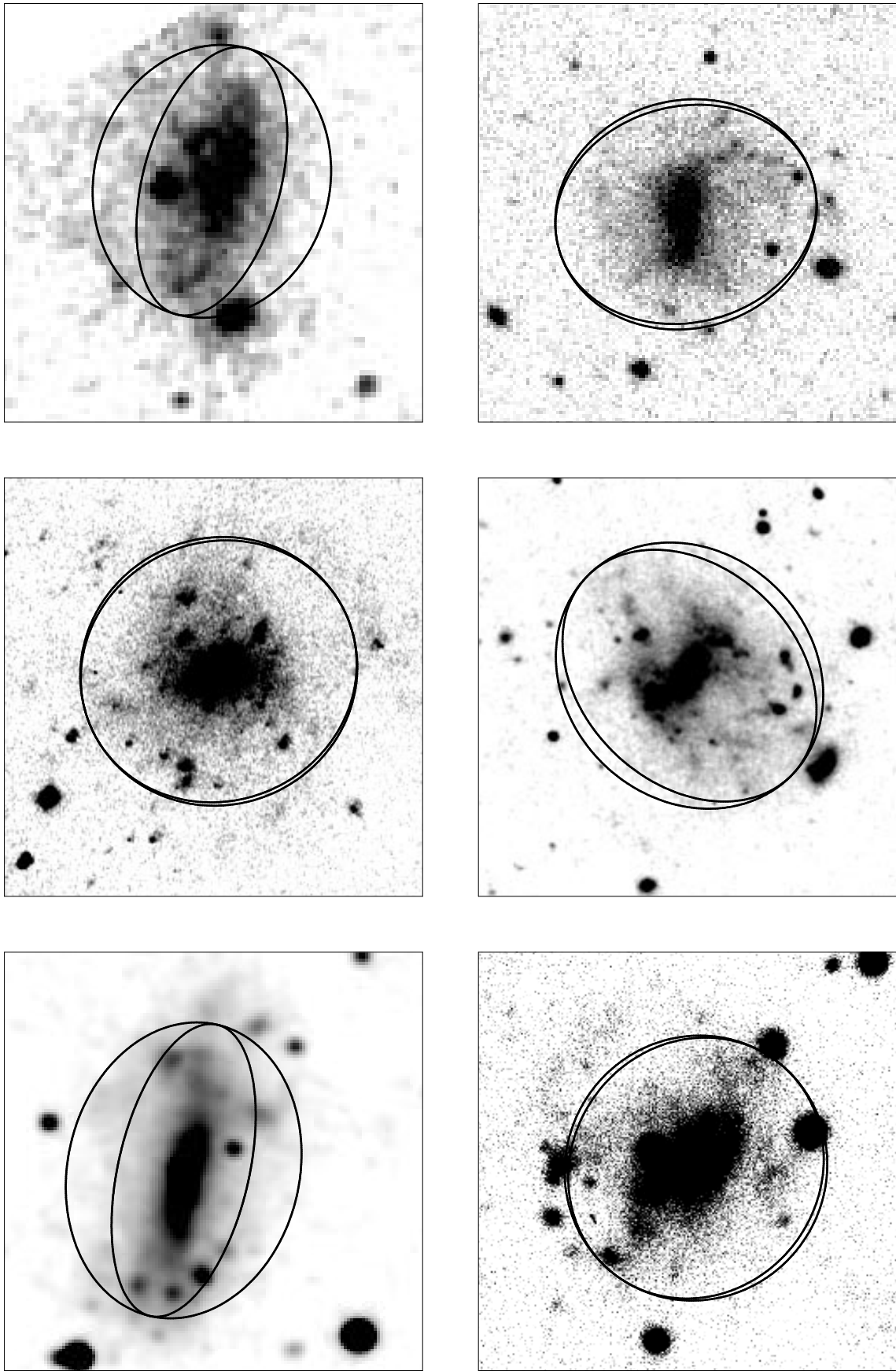


FIG. 2.—Optical *R*-band pictures of the six galaxies for which the assumed inclination had to be changed to get a good MOND fit: F565–V2 and F571–V1 (*top row*), U1230 and U5005 (*middle row*), and U5750 and U5999 (*bottom row*). The superimposed ellipses show the inclinations as derived in de Blok et al. (1996) and the MOND inclinations. In all cases, except for U5999, MOND prefers the lower inclination. See Table 1 for the exact values.

might be consistent with the H I column density map in van der Hulst et al. (1993), where one can derive an inclination of $\sim 35^\circ$ for the outermost column density contours. Deeper observations of this galaxy should be able to test this.

UGC 5999: MOND demands a value for the inclination of 22° instead of 14° . As shown in Figure 2, this results in only a very minor change in the axis ratios.

It is clear that in most cases the changes needed in the inclination to produce good fits are only minor. The only two challenging objects are F565–V2 and UGC 5750. To justify their inclinations, one needs in both cases a more face-on disk underlying the observed part of the galaxy. In both cases, deeper observations should provide more definite determinations of the inclinations. If these new values are still inconsistent with the MOND values, then this may be a problem for the theory.

It is striking that the fraction of barred galaxies in Figure 2 is much higher ($\sim 50\%$) than in the entire LSB sample ($< 10\%$). This may play some role in the inclination uncertainties. Also, note that the general preference is for slightly more face-on disks. This is expected for systematic errors introduced by finite thickness disks or deviations from purely circular shapes. In the rest of this paper we will adopt the new MOND inclinations and the corresponding results, but we will distinguish them from the “good” fits by using different symbols. In practice, the conclusions will not be affected.

3. RESULTS

The main result is that MOND is able to explain the slowly rising, nonflat rotation curves of galaxies with low surface brightnesses, where a large mass discrepancy is inferred in the classical, Newtonian case. The resulting stellar and total mass-to-light ratios enable us to derive some additional results which we will discuss below. In this discussion, we will also make use of the results of the MOND fits to the rotation curves of a large sample of HSB galaxies, presented in Sanders (1996).

3.1. The Tully-Fisher Relation and Mass-to-Light Ratios

MOND predicts a unique and exact *mass-velocity* relation $M_{\text{tot}} \propto V^4$, where M_{tot} denotes the total mass; that is, $M_{\text{tot}} = M_* + M_{\text{gas}}$. Converting this to more directly observable quantities yields

$$V^4 = G a_0 \left(\frac{M_{\text{tot}}}{L} \right) L. \quad (1)$$

The exact *M-V* relation thus translates into an identical *L-V* relation if M_{tot}/L is constant. Any scatter in M_{tot}/L will show up as scatter in the *L-V* relation (that is, as scatter in the TF relation).

MOND thus implies that there is a unique TF relation, where any scatter must be caused by scatter in M_{tot}/L . The small observed scatter in the TF relation thus implies there is only a small scatter in M_{tot}/L .

As discussed extensively in Papers I and II, in the classical dark-halo TF relation the only way to keep galaxies on the TF relation is by having a fine-tuned relation between the optical surface brightness of a galaxy and its total mass-to-light ratio (i.e., including the dark matter; Zwaan et al. 1995). In MOND all that is needed is that the scatter in M_{tot}/L is small enough to be consistent with the observed scatter in the TF relation.

In Figure 3 we show the *B*-band MOND TF relation for HSB galaxies as derived by Sanders (1996), with the LSB data superimposed. It is clear that there is no systematic offset between the HSB and the LSB galaxies. We now study the implied small scatter in M/L a bit more closely.

Figure 4 shows the stellar mass-to-light ratio $(M/L)_*$ and the total mass-to-light ratio M_{tot}/L as a function of maximum rotation velocity V_{max} , central surface brightness μ_0 , and color $B-V$.

The ratio $(M/L)_*$ overall is clearly increasing with V_{max} , consistent with the color-magnitude relation. The LSB galaxies are indistinguishable from the other galaxies, a situation which is in sharp contrast with the maximum disk results (de Blok & McGaugh 1997). There is no clear trend with central surface brightness, although the scatter increases toward lower surface brightnesses, which probably just reflects the large importance of the gas in these galaxies and the large effects that small amounts of star formation can have on the blue luminosity of LSB galaxies. This increase in scatter in $(M/L)_*$ is also apparent at the bluest $B-V$ colors. The values of $(M/L)_*$ are reasonable and vary between ~ 0 and ~ 5 (see Fig. 5). The distribution peaks at $(M/L)_* \sim 1$. The median of the HSB data equals 1.4, while that of the LSB data equals 1.3. Most fall within the range of $(M/L)_*$ predicted by population synthesis models (see Sanders 1996). No negative values of $(M/L)_*$ were found. MOND therefore does not overcorrect the mass-discrepancy. Measurements in the near-infrared, e.g., should yield $(M/L)_*$ values in a much smaller range, as tentatively indicated by Sanders (1996) and Sanders & Verheijen (1998).

The relevant parameter for the TF relation is, however, the *total* mass-to-light ratio, defined as $(M_{\text{gas}} + M_*)/L$. This quantity is also shown in Figure 4. A comparison with the $(M/L)_*$ data points shows that inclusion of the gas mass has made the increasing trend with V_{max} disappear. The ratio

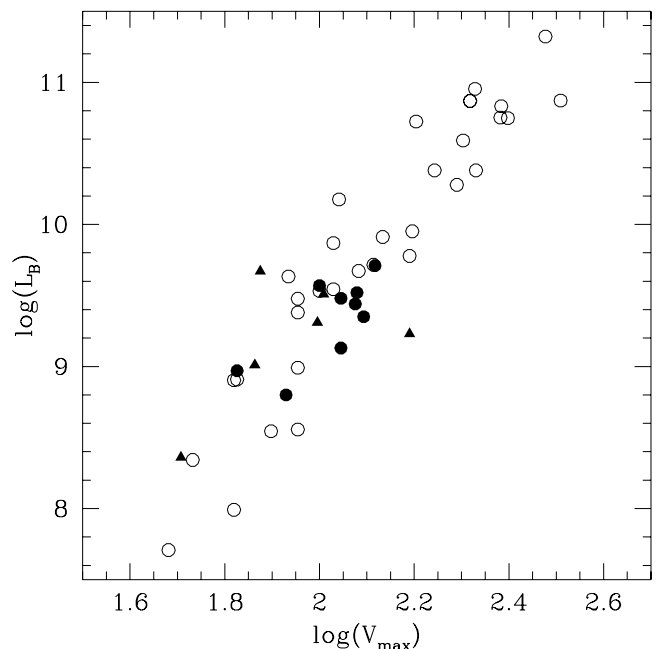


FIG. 3.—*B*-band TF relation for HSB and LSB galaxies. The open symbols show the data from Sanders (1996). The filled circles LSB galaxies where the inclination was not changed. The filled triangles represent the LSB galaxies where i had to be changed in order to get a good fit.

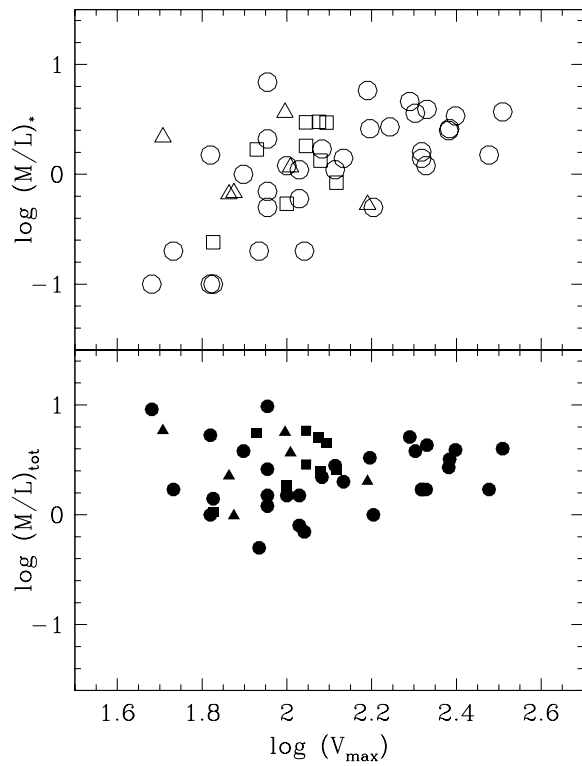


FIG. 4a

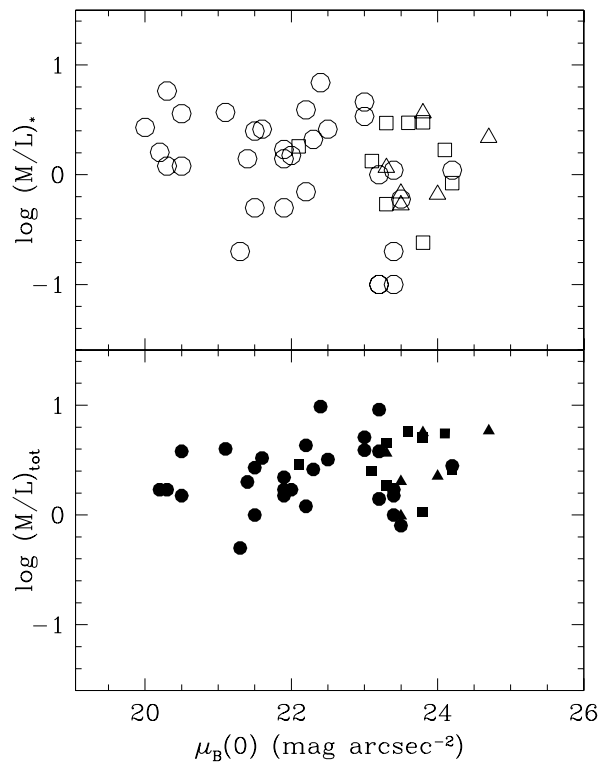


FIG. 4b

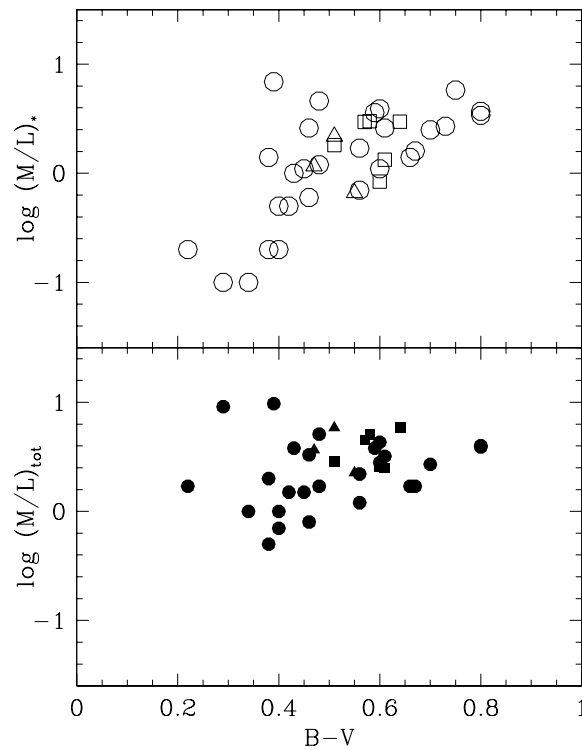


FIG. 4c

FIG. 4.—Mass-to-light ratios derived from the MOND fits, plotted against maximum rotation velocity derived from the rotation curves (*left*), against the central B -band surface brightness (*center*), and against $B-V$ color (*right*). Open symbols show the stellar mass-to-light ratio $(M/L)_*$, and filled symbols show the total mass-to-light ratio M_{tot}/L . The circles represent data from Sanders (1996). The squares represent LSB galaxies for which inclinations did not have to be changed. The triangles represent the six LSB galaxies where the inclination was changed.

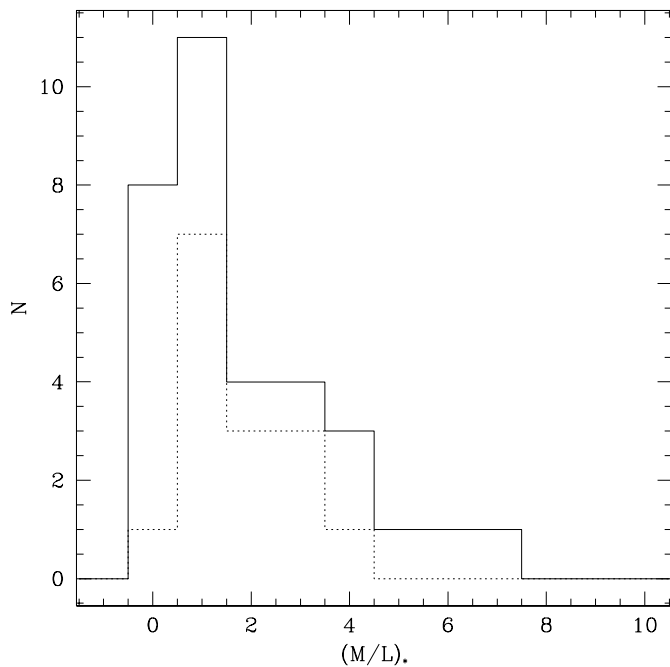


FIG. 5.—Histogram of the values of $(M/L)_*$ as found from fitting of rotation curves. The dotted histogram indicates the LSB data superimposed on the HSB data (solid line). The range and shape of both distributions is similar. Both peak between $(M/L)_*$ value of 0 and 1. The median of the HSB distribution is 1.4, and that of the LSB distribution is 1.3. Both distributions are consistent with values normally derived from population synthesis models.

M_{tot}/L does not show any systematic trend with V_{max} , $B-V$, and μ_0 . The gas mass thus makes a large contribution for low-luminosity and LSB galaxies. The average value of M_{tot}/L is 2.5. The dispersion in $\log(M_{\text{tot}}/L)$ is 0.30 dex, which compares to a dispersion in $\log L_B$ in the blue TF relation of 0.33 dex. The scatter in the TF relation is thus entirely consistent with, and can be explained by, the scatter in the values of M_{tot}/L .

The LSB galaxies in all respects confirm the predictions made by Milgrom (1983). These galaxies are deep in the MOND regime, with the lowest accelerations currently known. They provide the clearest and strongest test of MOND made to date.

4. DOES MOND FIT ANY ROTATION CURVE?

One of the myths surrounding MOND is that it is specifically designed to fit rotation curves and is therefore guaranteed to do so. Reality is a bit more complicated than this. MOND *predicts* what the rotation curve will be solely on the basis of the *observed* matter distribution. This is a fundamental difference from the dark matter theory, where a dark halo is fitted to whatever is left after the subtraction of the luminous component. The dark matter theory does not predict rotation curves, whereas in MOND there is a unique and unambiguous correspondence between the observed matter distribution and the rotation curve.

This results in MOND having much less freedom in getting the “right” answer than the dark matter rotation curve fits. This is already clear from fitting rotation curves of HSB galaxies. These show that the inner parts of HSB

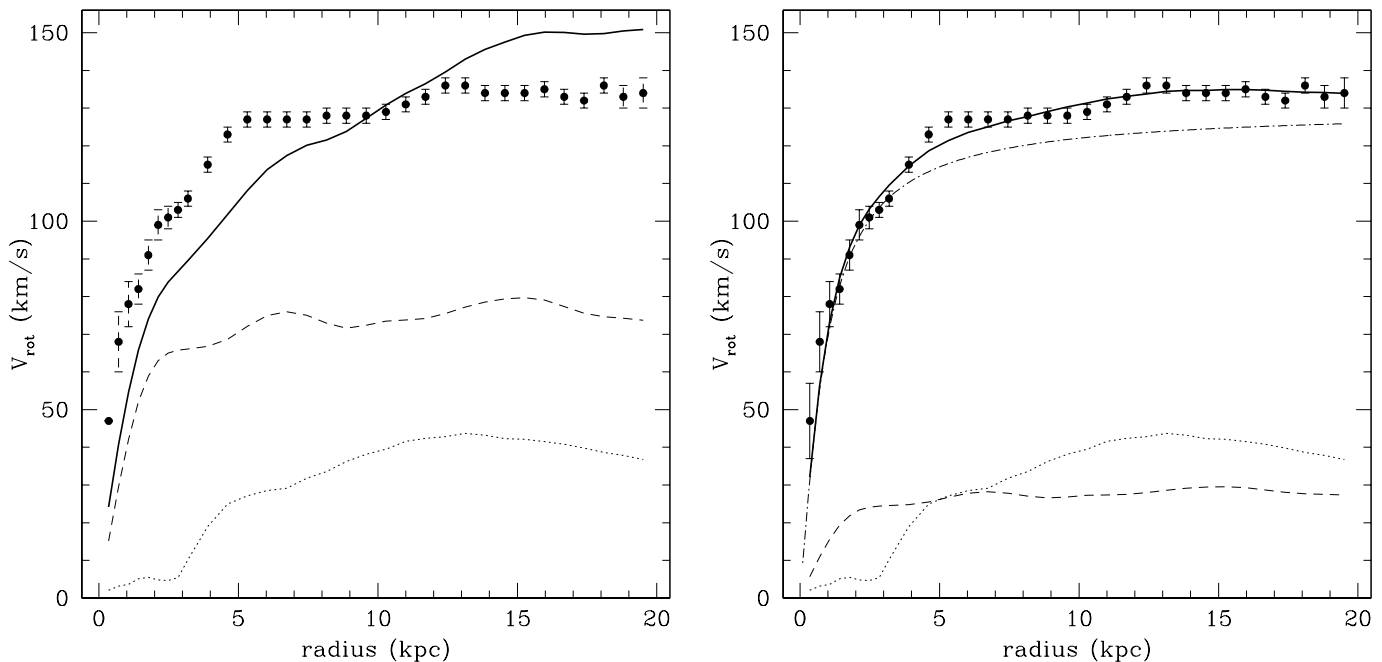


FIG. 6.—Fits of a hybrid NGC 2403/UGC 128 galaxy. This galaxy was constructed by using the NGC 2403 data, but replacing its photometry by that of UGC 128. The left panel shows the MOND result. MOND is unable to derive a good fit. The fit shown here has a_0 fixed and distance fixed at 3.3 Mpc. The value of $(M/L)_* = 6.0 \pm 0.5$. The right panel shows the classical fit with an isothermal dark matter halo. A good fit can be found with the following parameters: $(M/L)_* = 0.8 \pm 0.2$, and an isothermal halo with $R_C = 0.80 \pm 0.04$ kpc and $V_\infty = 130$ km s $^{-1}$ (fixed during fitting). The corresponding core density is $\rho_0 = 487 \times 10^{-3} M_\odot \text{pc}^{-3}$. The dotted line shows the gas rotation curve, and the dashed line shows the disk rotation curve. The long dashed line in the right panel shows the rotation curve. The heavy solid line in both panels is the final model rotation curve.

galaxies are still in the Newtonian regime and that therefore a Newtonian (i.e., “classical”) fit in these parts fixes $(M/L)_*$. Once $(M/L)_*$ is fixed, there is no more freedom in the fit. If the rotation curve in the outer parts does not exactly behave in the way MOND wants it to, then no good fits can be made.

We illustrate all of this by the following example: The HSB/LSB pair NGC 2403/UGC 128 are two galaxies that occupy identical positions on the TF relation, with indistinguishable luminosities and flat rotation amplitudes, but with very different central surface brightnesses. This is extensively described in de Blok & McGaugh (1996). In the classical, dark matter picture, the fact that these galaxies are on the same position on the TF relation means their mass distributions must be related. Whether this means that their halos are identical or not is unclear.

We will now construct a hybrid model galaxy by taking the rotation curve of NGC 2403, but where we will replace the optical photometry of NGC 2403 with that of UGC 128. This results essentially in an LSB version of NGC 2403. The similarity of the two galaxies maximizes the opportunity for both MOND and dark matter theories to achieve a fit to the hypothetical hybrid.

We have fitted this hypothetical galaxy with both the MOND and dark matter fitting procedures. We present the results in Figure 6. It is clear that in the MOND case no good fit can be made. The observed mass distribution is not related to the rotation curve, hence the bad fit. The implied stellar mass-to-light ratio is not reasonable, and both galaxies have rather high, well-determined inclinations so that adjusting the inclination within the errors will not have an impact on the procedure. In the dark matter case, one *can* reach a very tolerable fit, which is comparable in quality with the fit of the real NGC 2403 (see Begeman et al. 1991, their Fig. 1).

The conclusion we can reach from this is that MOND *cannot* fit any arbitrary rotation curve, dispelling the myth that asserts it was designed to do just this. MOND was designed to produce an asymptotically flat rotation curve, but this is no guarantee that the application of the MOND force law to the observed luminous mass distribution will obtain the correct shape for just any rotation curve. There must be a very close relation between the observed mass distribution and the rotation curve (both of which can be

determined independently), and this relation must be the MOND recipe if one wants to derive the latter solely from the former.

5. SUMMARY

The good fits to LSB galaxies rotation curves support MOND, especially because these are galaxies with large mass discrepancies in their observed disks, where the MOND effects are strongest.

The MOND fits furthermore *test* the MOND theory. This is not the case with dark matter fits, where the properties of the dark matter discrepancy are *derived* from the fits. These fits *define* the properties of the mass discrepancy. It is therefore not possible to falsify nor confirm the dark matter hypothesis from rotation curves alone, as can be done with the MOND hypothesis. We show this by fitting a hypothetical nonphysical galaxy: the MOND theory is unable to produce a good fit (which in this case is a good thing), whereas we can get a good fit with the dark matter theory (showing it is more flexible in fitting nonphysical models).

In principle, there are an infinite number of things the rotation curves of galaxies could do given the presence of an invisible mass component. There are many plausible predictions for what they are expected to do given various ideas about dark matter. In the case of MOND, there is one and only one thing rotation curves can do. This is precisely what they do.

One last remarkable result is the great efficiency with which MOND can describe the rotation curves of galaxies of very different types. Even if MOND is ultimately falsified, it would still be worth knowing why it works so well. Until a MOND cosmology can be derived (see Sanders 1998), it remains a recipe for describing rotation curves, but as a recipe it is far superior to the dark halo recipe; this raises the question of *why* MOND works so well. MOND is after all only a simple analytic formula that gets $V(R)$ correct based solely on the luminous mass. If the MOND phenomenology arises as the result of dark matter, then this would imply that the dark matter must “know” about both the distribution of light *and* the MOND formula and arrange itself appropriately, right down to amplifying the bumps and wiggles in the stellar and gas rotation curves by the appropriate amount.

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