Galaxy Mass Models: MOND versus Dark Matter Halos

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ABSTRACT

Mass models of 15 nearby dwarf and spiral galaxies are presented. The galaxies are selected to be homogeneous in terms of the method used to determine their distances, the sampling of their rotation curves (RCs) and the mass–to–light ratio (M/L) of their stellar contributions, which will minimize the uncertainties on the mass model results. Those RCs are modeled using the M0dified Newtonian Dynamics (MOND) prescription and the observationally motivated pseudo-isothermal (ISO) dark matter (DM) halo density distribution. For the MOND models with fixed (M/L), better fits are obtained when the constant a0 is allowed to vary, giving a mean value of (1.13 ± 0.50) × 10−8 cm s−2, compared to the standard value of 1.21 × 10−8 cm s−2. Even with a0 as a free parameter, MOND provides acceptable fits (reduced χ² < 2) for only 60 % (9/15) of the sample. The data suggest that galaxies with higher central surface brightnesses tend to favor higher values of the constant a0. This poses a serious challenge to MOND since a0 should be a universal constant. For the DM models, our results confirm that the DM halo surface density of ISO models is nearly constant at ρ0 Rg ∼ 120 M⊙ pc−2. This means that if the (M/L) is determined by stellar population models, ISO DM models are left with only one free parameter, the DM halo central surface density.

Key words: Cosmology: dark matter; galaxies: kinematics and dynamics

1 INTRODUCTION

Since the 1970’s, it is well known that there is a discrepancy between the visible mass and the dynamical mass of galaxies (e.g. Freeman 1970; Shostak 1973; Roberts & Whitehurst 1975; Bosma 1978). The commonly accepted explanation of the galaxy mass discrepancy is to assume a more or less spherical halo of unseen dark matter in addition to the visible baryonic mass in the form of stars and gas (see e.g. Carignan & Freeman 1985). The distribution of dark matter in galaxies can be defined by a theoretical or an empirical density distribution profile. Several density profile models for the distribution of dark matter (DM) are presented in the literature. The two most commonly used models are (see also e.g. Einasto 1969; Burkert 1995; Kravtsov et al. 1998):

- the pseudo-isothermal (ISO) dark matter halo model (observationally motivated model)
- the Navarro-Frenk-White (NFW) dark matter halo model (Navarro et al. 1997) (derived from ΛCDM N-body simulations)

The highest quality H I RC s (RCs) available to date are those for the THINGS (The Hi Nearby Galaxies Survey) sample (Walter et al. 2008). For that sample, the RCs of 19 galaxies were derived by de Blok et al. (2008) and their mass distributions were modeled using the ISO and the NFW halo density profiles. de Blok et al. (2008) found that most of the galaxies in their sample preferred the observationally motivated core-dominated ISO halo over the cuspy NFW halo. This is known as the core-cusp controversy (see de Blok 2010 for a review). This is why the ISO models will be used in this paper for the DM models.

An alternative to the missing mass problem is the M0dified Newtonian Dynamics (MOND) (Milgrom 1983). Milgrom postulates that at small accelerations the usual Newtonian dynamics break down and that the law of gravity needs to be modified. MOND claims to be able to explain the mass discrepancies in galaxies without the need for dark matter but with the introduction of a universal constant a0, which has the dimension of an acceleration.

The phenomenological success of MOND to reproduce the observed RCs of galaxies has attracted a huge interest in the astronomy community for the last three decades. One of the first studies was made by Kent (1987) using H I RCs of spiral galaxies and his conclusions were not favorable to MOND. Kent’s work was criticized by Milgrom (1988) who pointed out possible errors in the distances and inclinations used and the possibility that not all the HI gas had been detected.

Dwarf galaxies are critical to test a theory such as MOND because these objects present the largest discrepancies between the visible mass and the dynamic mass and their small accelerations put them mostly into the MOND regime. Lake (1985) concluded that MOND could not reproduce the observed RCs of a sample of...
dwarf galaxies where the luminous mass was dominated by the gas and not the stars. However, Milgrom (1991) disapproved Lake’s conclusions arguing again that there could be large errors in the distances and inclinations.

Begeman et al (1991) were the first to estimate the value of $a_0$ by fitting the RCs of bright spiral galaxies. The MOND parameter $a_0$ was taken as a free parameter during their fitting procedure. They found an average value of $a_0 = 1.21 \times 10^{-8}$ cm s$^{-2}$. However, the distances used were quite uncertain since Hubble’s Law was adopted as the distance indicator for most of the galaxies in their sample. The Begeman et al. (1991) results were confirmed by Sanders (1996) and Sanders & Verheijen (1998) using the same method. Sanders (1996) used a larger sample of 22 galaxies selected from the literature but only M33 and NGC 300 had cepheid distances. Since then, the value found by Begeman et al. (1991) is considered as the standard value for $a_0$. Bottema et al. (2002) were the first to use a sample with cepheid-based distances only and found that a lower value for $a_0$ ($0.9 \times 10^{-8}$ cm s$^{-2}$) yields better fits to the RCs. A complete review about the previous tests of MOND is presented in Sanders & McGaugh (2002). In that review the basic framework of MOND is explained. RCs fits using MOND prior to 2002 are presented and the different capabilities of MOND are listed. The most recent review on MOND and its implications for cosmology can be found in Famaey & McGaugh (2012).

The analysis by de Blok & McGaugh (1998) was the first to use LSB galaxies in the context of MOND. Those systems are good candidates to test MOND because their accelerations fall below the MOND acceleration limit $a_0$. de Blok & McGaugh (1998) used a sample of 15 LSB galaxies. They found that MOND is successful to reproduce the shape of the observed RCs for three quarters of the galaxies in the sample. The most recent study of LSB galaxies in the context of MOND was done by Swaters et al. (2010). MOND produced acceptable fits for also three quarters of the galaxies in their sample. The correlation between $a_0$ and the extrapolated central surface brightness of the stellar disk was also investigated. Swaters et al. (2010) found that there might be a weak correlation between $a_0$ and the R-band central surface brightness of the disk. This is shown in their Figure 7. Their interpretation was that galaxies with lower central surface brightness had lower values for $a_0$. Such a correlation would be in contradiction with MOND since $a_0$ should be an universal constant. The reliability of the MOND mass models depends strongly on the sensitivity and spatial resolution of the observed RCs. More extended RCs are needed to trace the matter up to the edge of the galaxies but higher resolution is required in the inner parts.

RCs derived from the THINGS sample satisfy these criteria. THINGS consists of 34 dwarfs and spiral galaxies observed in Hα with the Very Large Array in the B, C and D configurations (Walter et al. 2008). Gentile et al. (2011) used a subsample of 12 galaxies from de Blok et al. (2008) and modeled their mass distributions using the MOND formalism. They performed one and two parameter MOND fits and recalculated the value of $a_0$ which turned out to be similar to the standard value estimated in Begeman et al. (1991). Their average value for $a_0$ is $1.22 \times 10^{-8}$ cm s$^{-2}$ using the simple $\mu$-function (Zhao & Famaey 2006) for the interpolation between the Newtonian and the MONDian regimes. They also looked at the correlation between $a_0$ and central surface brightness in the 3.6 micron band and found that there was no correlation. However their points have a large scatter and they used the bulge central surface brightness instead of the extrapolated disk central surface brightness.

Slowly rotating gas rich galaxies are good candidates to test MOND because their accelerations are below $a_0$ and the baryonic mass is dominated by gas and not stars. Sánchez-Salcedo et al. (2013) studied a sample of five such galaxies and found significant departures between the observed RCs and the ones predicted by MOND (see also Frusciani et al. 2012). Recently, Carignan et al. (2013) presented a detailed study of the magellanic-type spiral galaxy NGC 3109 using VLA Hα data from Robijn & Carignan (1990) and new data from the SKA pathfinder KAT-7 telescope in the Karoo desert in South Africa. With both data sets, they found that MOND cannot fit the observed RC of NGC 3109, while their distance and inclination are well determined. On the other hand, the ISO dark matter halo model gives a very good fit to both data sets.

A sample of fifteen galaxies, mostly with cepheid-based distances, will be used for the present study with the aim to minimize the errors coming from the adopted distance. Some RCs have been resampled to have a homogeneous sample of RCs with independent velocity points in order to give significance to the goodness of the fits of the mass models. The (M/L)s used have also been determined in a homogeneous way using stellar population models predictions, instead of leaving them as free parameters.

This paper is organized as follows: the sample selection is presented in section 2, the methods used for the mass models are explained in section 3, results are shown in section 4, followed by the discussion in section 5 and the conclusions in section 6.

## 2 SAMPLE

The two main selection criteria for the final sample of 15 dwarf and spiral galaxies are the method used to determine their distance and the availability of high quality Hα RCs in terms of spatial resolution and sensitivity. Cepheid based distances, using their period-luminosity relation, are commonly considered as the most accurate for nearby galaxies. We were able to use this method for all but two of the galaxies in the sample. The method used to measure the distance and references are given in column 5 of table 1.

Another criteria is to have a sample of galaxies spanning a wide range of luminosities and morphological types from dwarf irregular to bright spiral galaxies. Therefore DDO 154 and IC 2574 are included even if Cepheid distances are not available. Furthermore, these two galaxies are gas dominated galaxies and exhibit large discrepancies between their visible mass and their dynamical mass which makes them ideal objects to test MOND and DM halo models.

Eleven galaxies of the final sample are part of THINGS, their RCs being derived by de Blok et al. (2008). For the others, the RCs and gas distributions are taken from Carignan et al. (2013) for NGC 3109, from Westmeier et al. (2011) for NGC 300, from Puche et al. (1991) for NGC 55 and from Carignan & Puche (1996) for NGC 247. There is considerable overlap between the sample used in this work and Gentile et al. (2011), 7 out of 15 galaxies are common to both studies. However, IC 2574, NGC 925 and NGC 2366 are included in this study, which were omitted by Gentile et al. (2011) because of the presence of holes and shells and non-circular motions. The RCs of these galaxies were derived using the bulk velocity fields only (Oh et al. 2008) which remove the effect of holes and shells. The presence of small bar could also introduce mild distortion, but that is beyond the scope of this study and will be investigated in an upcoming paper which will investigate the non-circular motions induced by the bar as a function of the size and orientation of the bar using numerical simulation.
Table 1. Properties of the galaxies in the sample

| Name     | P. A. | Incl. | Distance | Method [Ref] | \(m_B\) | \(M_B\) | Type       |
|----------|-------|-------|----------|--------------|---------|---------|------------|
| DDO 154  | 230   | 66    | 4.30 ± 0.54 | bs [K04]     | 13.94  | -14.23 | IB(s)m     |
| IC 2574  | 53.4  | 55.7  | 4.02 ± 0.41 | rgb [K04]    | 10.80  | -17.21 | SAB(s)m    |
| NGC 0055 | 109.7 | 76.9  | 1.94 ± 0.03 | cep [G08]    | 9.60   | -16.79 | SB(s)m     |
| NGC 0247 | 170.0 | 74.0  | 3.41 ± 0.17 | cep [G09]    | 9.70   | -17.95 | SB(s)cd    |
| NGC 0300 | 310.5 | 42.3  | 1.99 ± 0.04 | cep [G05]    | 8.72   | -17.67 | SA(s)d     |
| NGC 0925 | 286.6 | 66.0  | 9.16 ± 0.63 | cep [F01]    | 10.69  | -19.13 | SAB(s)d    |
| NGC 2366 | 39.8  | 63.8  | 3.44 ± 0.31 | cep [T95]    | 11.53  | -16.13 | IB(s)m     |
| NGC 2403 | 123.7 | 62.9  | 3.22 ± 0.14 | cep [F01]    | 8.93   | -18.60 | SAB(s)cd   |
| NGC 2841 | 152.6 | 73.7  | 14.10 ± 1.50| cep [F01]    | 10.09  | -20.66 | SA(r)b     |
| NGC 3031 | 330.2 | 59.0  | 3.63 ± 0.25 | cep [F01]    | 7.89   | -19.89 | SA(s)ab    |
| NGC 3109 | 93.0  | 75.0  | 1.30 ± 0.02 | cep [S06]    | 10.39  | -15.18 | SB(s)m     |
| NGC 3198 | 215.0 | 71.5  | 13.80 ± 0.95| cep [F01]    | 10.87  | -19.83 | SB(rs)d    |
| NGC 3621 | 345.4 | 64.7  | 6.64 ± 0.46 | cep [F01]    | 10.28  | -18.82 | SA(s)d     |
| NGC 7331 | 167.7 | 75.8  | 14.72 ± 1.02| cep [F01]    | 10.35  | -20.49 | SA(s)b     |
| NGC 7793 | 290   | 50    | 3.43 ± 0.10 | cep [P10]    | 9.17   | -18.79 | SA(s)cd    |

bs: brightest stars, rgb: red giant branch, cep: cepheid variables; F01: Freedman et al. (2001); S06: Soszyński et al. (2004); K04: Karachentsev et al. (2004); T95: Tolstoy et al. (1995); P10: Pietrzyński et al. (2010); G05: Gieren et al. (2005); G08: Gieren et al. (2008); G09: Gieren et al. (2009)

col. 1: Galaxy name; col. 2: Position Angle; col. 3: Inclination; col. 4: Distance with the uncertainty; col. 5: Method used to measure the distance & reference; col. 6: Apparent magnitude taken from the RC3 catalog; col. 7: Absolute magnitude; col 8: Morphology type.

3 MASS MODELS

3.1 Mass Models with a Dark Matter Halo

As mentioned in the introduction, most of the mass in the galaxies appears to be in the form of unseen matter called Dark Matter (DM), whose existence is inferred through its gravitational effect on luminous matter such as the flatness of RCs or the gravitational lensing effect. The common scenario is that galaxies are embedded in dark matter halos which follow some density distribution profile. In this paper, the observationally motivated pseudo-isothermal dark matter halo profile (ISO), characterized by a constant central density core, will be used.

A mass model compares the observed RC to the sum of the contributions of the three mass components, namely the gas disk, the stellar disk (and bulge, if present) and the dark halo. It is well known that neutral hydrogen usually has a larger radial extent compared to the luminous part of the galaxy, especially for late-type spirals and dwarf irregular galaxies (at least in the field). Therefore the RC derived using the HI gas traces the mass of the galaxy to larger radii. The contributions of all the components are required for the mass model. The stellar components used in this study are derived from 3.6 micron surface brightness profiles, converted into mass using the mass-to-light ratio (M/L) in that particular band. This M/L is assumed to be constant with radius (cf. section 3.3.2). Most of the gas content of the galaxy is in the form of neutral hydrogen, thus the gas contribution is derived from the HI maps corrected for the primordial helium contribution. The dark matter halo component is derived from the pseudo-isothermal density distribution.

The RC is thus given by the quadratic sum of the contribution from each component:

\[
V_{\text{rot}}^2 = V_{\text{gas}}^2 + V_{\text{*}}^2 + V_{\text{halo}}^2
\]

where \(V_{\text{gas}}\) is the gas contribution, \(V_{\text{*}}\) the stars contribution and \(V_{\text{halo}}\) the contribution of the dark matter component.

The pseudo-Isothermal (ISO) Dark Matter (DM) Halo Model

For the pseudo-isothermal dark matter halo, the density distribution is given by:

\[
\rho_{\text{ISO}}(R) = \frac{\rho_0}{1 + \left(\frac{R}{R_c}\right)^2}
\]
while the corresponding RC is given by:

\[ V_{ISO}(R) = \sqrt{\frac{4\pi G \rho_0 R_c^2}{1 - \frac{R}{R_c}} \tan\left(\frac{R}{R_c}\right)} \]

(3)

where \( \rho_0 \) and \( R_c \) are the central density and the core radius of the halo, respectively. We can describe the steepness of the inner slope of the mass density profile with a power law \( \rho \sim r^\alpha \). In the case of the ISO halo, where the inner density is an almost constant density core, \( \alpha = 0 \).

### 3.2 Mass Models using the MOND formalism

MOND was proposed by Milgrom as an alternative to dark matter. Therefore, in the MOND formalism only the contributions of the gas and of the stellar component are required to explain the observed RCs.

In the MOND framework, the gravitational acceleration of a test particle is given by:

\[ \mu(x = g/a_0)g = g_N \]

(4)

where \( g \) is the gravitational acceleration, \( \mu(x) \) is the MOND interpolating function and \( g_N \) the Newtonian acceleration.

#### 3.2.1 MOND Acceleration Constant \( a_0 \)

As an universal constant, \( a_0 \) should be the same for all astrophysical objects. However, observational uncertainties could introduce a large scatter in \( a_0 \) and have to be taken into account. Significant departures of \( a_0 \) from the standard value could be interpreted as being problematic for MOND. Milgrom estimated \( a_0 \) using Freeman’s law, which stipulates that disk galaxies have typical extrapolated central surface brightness in the B band (Freeman 1970) of 21.65 mag arcsec\(^{-2}\). He estimated \( a_0 \) to be \( \sim (0.7 - 3) \times 10^{-8} (M/L)_\odot \) cm s\(^{-2}\). There are other methods which could be used to find \( a_0 \), such as the Tully-Fisher relation. However, the preferred method, used in many studies, is to estimate \( a_0 \) by comparing the computed RCs from mass models to the observed RCs, leaving \( a_0 \) as a free parameter. The implications of \( a_0 \) in cosmology are explained in Famaey & McGaugh (2012).

#### 3.2.2 MOND Interpolating Functions

The shape of the predicted MOND RCs depends on the interpolating function. The standard and simple interpolating functions are mostly used in the literature. The standard \( \mu \)-function is the original form of the interpolating function proposed by Milgrom (1983a) but Zhao & Famaey (2006) found that a simplified form of the interpolating function not only provides good fits to the observed RCs but also the derived mass-to-light ratios are more compatible with those obtained from stellar populations synthesis models. The simple \( \mu \)-function is given as:

\[ \mu(x) = \frac{x}{1 + x} \]

(5)

The MOND RC using the simple interpolating function is given by

\[ V_{rot}^2 = \sqrt{V_{*,d}^2 + V_{*,b}^2 + V_{g}^2} \sqrt{a_0 \ast r + V_{*,d}^2 + V_{*,b}^2} \]

(6)

where \( V_{*,d}, V_{*,b}, V_g \) are the contributions from the stellar disk, the bulge and the gas to the RC.

### 3.3 Luminous Component Contribution

#### 3.3.1 Gas Contribution

VLA observations using combined B, C and D array configurations data (Walter et al. 2008) are used to compute the mass density profile of the H\(_i\) gas for the THINGS galaxies. It is computed using the GIPSY task ELLINT and the tilted ring kinematical parameters from de Blok et al. (2008). The H\(_i\) profile is corrected by a factor of 1.4 to take into account the Helium and other metals. The output from ELLINT is then used in ROTMOD to calculate the gas contribution in the mass model, assuming an infinitely thin disk. The gas density profiles are taken from Westmeier et al. (2011) for NGC 300 using ATCA data and from Carignan et al. (2013) for NGC 3109 using KAT7 data, from Puche et al. (1991) for NGC 55 and from Carignan & Puche (1990) for NGC 247, using VLA data.

#### 3.3.2 Stellar Contribution

For the mass models, the 3.6 micron surface brightness profiles are used for the stellar contribution. 3.6 micron probes most of the emission from the old stellar disk population (Verheijen 1997). It is also less affected by dust and therefore represents the bulk of the stellar mass. The profiles from de Blok et al. (2008) are used for the galaxies from the THINGS sample. The profiles were decomposed into two components for the galaxies with a prominent central bulge (see de Blok et al. 2008 for more details). The 3.6 micron surface brightness profiles of NGC 55 and NGC 247 are derived in this work. The images were retrieved from the Spitzer Heritage Archive using a 0.6 arcsec/pixel scale. After removing the foreground stars, the images were fitted with concentric ellipses using the ELLIPSE task in IRAF. These profiles are corrected for inclination before being converted into mass density. The method from Oh et al. (2008) is adopted to convert the luminosity profiles into mass density profiles for all the galaxies in the sample except for NGC 300 and NGC 3109. Oh et al. (2008) first convert the surface brightness profiles in mag/arcsec\(^2\) into luminosity density profiles in units of L\(_\odot\)/pc\(^2\) and then convert to mass density using the following expression:

\[ \Sigma[M/L_\odot pc^{-2}] = (M/L)_\odot^{3.6} \times 10^{-0.4 \times (\mu_{3.6} - C^{3.6})} \]

(7)

where \((M/L)_\odot^{3.6}\) is the stellar mass-to-light ratio in the 3.6 micron band, \(\mu_{3.6}\) the surface brightness profile and \(\Sigma[M/L_\odot pc^{-2}]\) is a constant used for the conversion from mag/arcsec\(^2\) to L\(_\odot\)/pc\(^2\). The details to find \(\mu_{3.6}\) are presented in Oh et al. (2008):

\[ C^{3.6} = M_{\odot}^{3.6} + 21.56 \]

(8)

where \(M_{\odot}^{3.6}\) is the absolute magnitude of the Sun in the 3.6 micron band. Using the distance modulus formula and the distance to the Sun, Oh et al. (2008) found:

\[ M_{\odot}^{3.6} = M_{\odot}^{4.6} + 31.57 = 3.24 \]

(9)

The mass density profile of NGC 300 is taken from Westmeier et al. (2011). For NGC 3109, the I-band profile is used instead of the 3.6 microns because it has a larger radial extent.

#### 3.3.3 Mass to light ratio (M/L)

The conversion of light into mass through the mass-to-light ratio (M/L) is the principal source of uncertainty in the mass model.
Therefore, the determination of this parameter should not be taken lightly or left as a free parameter. In this work, the stellar synthesis models of Bell & de Jong (2001) are used. As mentioned by de Blok et al. (2008), the uncertainties on (M/L) decrease in the infrared band. Therefore, the (M/L) derived in the infrared band will be used when available.

The method of Oh et al. (2008) is followed. The (M/L) at 3.6 micron is given by:

\[
\log(M/L_k) = 1.46(J - K) - 1.38
\]

and

\[
(M/L)_{J,6} = 0.92(M/L)_k - 0.05
\]

The J-K colors are those from the 2MASS Large Galaxy Atlas (Jarrett et al. 2003). An I-band M/L of 0.7 predicted by the stellar population synthesis models is adopted for NGC 3109.

4 RESULTS

The HI RCs of the THINGS sample are oversampled with two data points per resolution element. If we want the reduced \(\chi^2\) values to be meaningful, the RCs have to be resampled with only one point per beam, so that every point is independent. Therefore, resampled versions of the THINGS HI RCs and of four other RCs from the literature will be used to construct the mass models of the galaxies in our sample. The gas and stellar contributions to the RCs are computed with the GIPSY task ROTMAS. The outputs from ROTMAS are used in ROTMAD, which is the main task for the mass models. ROTMAS uses a non-linear least square method and compares the observed RCs to the calculated RCs derived from the observed mass distribution of the gas and stars (van der Hulst et al. 1992). Inverse squared weighting of the RCs’ data points with their uncertainties are used during the fitting procedure.

4.1 ISO Dark Matter Halos Fit Results

Dark matter mass models are shown in the left panels of Figs. 1. The dark matter halo components are shown as dashed magenta lines, the contribution from the stellar disk components as dot-dashed black lines, the stellar bulge components as long-dashed green lines and that from the gas components as dashed red lines. The results are summarized in Table 2.

4.2 MOND Results

4.2.1 MOND fits with distance fixed

The MOND models were performed with the same (M/L)s as the ones used for the DM models. MOND fits are shown in the middle panels of Figs. 1 for \(a_0\) fixed at its standard value and in the right panels for \(a_0\) free. The observed RCs are shown as black points with error-bars and the MOND RCs calculated from the observed mass density distribution of the stars and gas in continuous blue lines. The stellar disk and bulge contributions are shown as black dot-dashed and long-dashed lines respectively and the gas contributions as red dashed lines. Results for the \(a_0\) fixed and \(a_0\) free fits are also shown in Table 2. An average value for \(a_0\) of \((1.13 \pm 0.50) \times 10^{-8}\) cm s\(^{-2}\) is found using the simple interpolating function. As for Bottura et al. (2002), this is smaller than the standard value of Begeman et al. (1991).

4.2.2 MOND fits with distance let free to vary within the uncertainties

The distance was allowed to vary within the uncertainties in the case of galaxies in which MOND produces poor fits to their RCs. The results are shown in Table 3.

5 DISCUSSION

The average reduced chi-square for the ISO halo \((<\chi^2_r>=1.18)\) is lower than that obtained from MOND with fixed \(a_0 (<\chi^2_r>=9.20)\) using the distance listed in Table 1 and even when \(a_0\) is allowed to vary \((<\chi^2_r>=2.37)\). Discrepancies between the RCs predicted by MOND and the observed RCs are seen for most of the galaxies in the sample and particularly for DDO 154, IC 2574, NGC 925, NGC 2841, NGC 3109, NGC 3198 and NGC 7793, in which MOND overestimates or underestimates the rotation velocities. The difference between the MOND fits and the observed RCs is smaller for the following galaxies: NGC 0055, NGC 2366, NGC 3621 and NGC 7331 when \(a_0\) is fixed to its canonical value. Notes on the individual galaxies are given in the appendix, where the results from this study are compared to those in the literature.

5.1 Effect of varying the adopted distances within the uncertainties

The results are summarized in Table 3. The adopted distances are different with Gentile et al. (2011) for the following galaxies: DDO 154 (the error-bars are not the same), NGC 2403, NGC 3198 (the error-bars are not the same) and NGC 7793. MOND prefers lower distances for most of the galaxies except for NGC 247, NGC 2403, NGC 2841 and NGC 7793. It is worth noticing that a much lower distance is needed for some galaxy such as NGC 3198 if the M/L is fixed. The quality of the fits improves when the MOND acceleration constant \(a_0\) is taken as a free parameter for all the galaxies.

5.2 Comparison with previous work

There are a wealth of studies on MOND in the literature, but this section will focus on a comparison between this work and that of Gentile et al. (2011) because, not only Gentile et al. (2011) is the most recent study, but both samples have a large overlap. The main difference between this work and Gentile et al. (2011) is that in this work, MOND produces acceptable fits for \(\sim 60\%\) of the galaxies in the sample, while Gentile et al. (2011) found that MOND produces excellent fits for all the galaxies except for three (DDO 154, NGC 2841 and NGC 3198), meaning for \(\sim 75\%\) of their sample. The similarity between this paper and Gentile et al. (2011) is that seven galaxies are common in both studies. For those seven galaxies, five galaxies produce acceptable MOND fits when \(a_0\) was left free to vary. The differences stem from two main reasons:

- First, Gentile et al. (2011) allowed the mass-to-light ratio to vary and the distances were constrained within the errors, which gave smaller chi-squared values. In this work, the mass-to-light ratios are fixed using those found using population synthesis models.
- Second, the distance used in this work and Gentile et al. (2011) are not the same, for example the distance adopted in this work for NGC 2403 is \((3.22 \pm 0.14)\) Mpc, as listed in Table 1 while their distance is \((3.47 \pm 0.29)\) Mpc. Our distances are mainly cepheid-based.
Figure 1. Mass model fit results, left panel: ISO RCs fits (the parameter results are in Table 2), middle panel: MOND RCs fits with $a_0$ fixed and right panel: MOND RCs fits with $a_0$ free (the MOND parameter results are in Table 3). The red dashed curve is for the HI disk, the dash-dotted black curve is for the stellar disk, dashed green curves for the stellar bulge and the dashed magenta curves for the dark matter component. The bold blues lines are the best-fit models and the black points the observed rotational velocities.
Figure 1. Continued.
Figure 1. Continued.
However, this work would reach the same conclusions as Gentile et al. (2011) if the mass-to-light ratio was also a free parameter and the distances only constrained. It is well known that the more you have free parameters, the easier it is to get good fits. This is why Gentile et al. (2011) get 75% (9/12) good fits with their distance constrained option and free mass-to-light ratios, while this falls to 60% (9/15) when the distance and mass-to-light ratio are fixed. The difference between the two studies is probably not significant given the small sample sizes in both studies.

5.3 Correlation Between the MOND Acceleration Constant $a_0$ and other Galaxy Parameters

Any systematic trend of $a_0$ with some galaxy parameter could be a problem for MOND since it is supposed to be a universal constant. Here, we look for a correlation between the corrected central surface brightness of the stellar disk with the MOND parameter $a_0$. As shown in Fig. 2, galaxies with higher central surface brightness require higher values of $a_0$ and galaxies with lower central surface brightness lower $a_0$ values. This has also been seen in the R-band for LSB galaxies by Swaters et al. (2010). Gentile et al. (2011) did the same analysis using the 3.6 micron band for twelve (12) galaxies from the THINGS sample and did not find any correlation. However, the bulge central surface brightnesses were used for their study instead of the disk values. Five galaxies in their sample (see their figure 2) have central surface brightnesses brighter than 13.5 mag/arcsec$^2$ which are probably due to the small but bright central bulges. The surface brightness profile increases sharply within a small radius and lead to a very high estimated central surface brightness, which is the reason why the extrapolated disk central surface brightness have to be used. The following relation is found
Table 2. Results for the ISO dark matter halo models with fixed M/L (Diet-Salpeter IMF) and for the MOND models using \(a_0 = 1.21 \times 10^{-8}\) cm s\(^{-2}\) and \(a_0\) as a free parameter (simple interpolating function).

| Name    | (M/L)\(_{3.6, disk}\) | (M/L)\(_{3.6, bulge}\) | \(R_C\)   | \(\rho_0\)     | \(\chi^2_r\) \(a_0\) fixed | \(\chi^2_r\) \(a_0\) free |
|---------|----------------------|----------------------|----------|------|-----------------|-----------------|
| DDO 154 | 0.32 [dB08]          | 1.34 ± 0.07          | 27.38 ± 2.33 | 0.42 | 6.32 ± 0.08  | 0.56 ± 0.02    |
| IC 2574 | 0.44 [dB08]          | 7.36 ± 0.21          | 4.02 ± 0.22 | 0.22 | 19.28 ± 0.36 | 1.87 ± 0.02   |
| NGC 0055| 0.44 [Tw]            | 3.17 ± 0.12          | 19.19 ± 0.88 | 0.36 | 1.53 ± 0.05  | 1.78 ± 0.05   |
| NGC 0247| 0.36 [Tw]            | 1.63 ± 0.08          | 55.45 ± 3.88 | 1.59 | 6.06 ± 0.14  | 3.31 ± 0.05   |
| NGC 0300| 0.27 [W11]           | 1.08 ± 0.15          | 117.93 ± 29.63 | 1.78 | 5.43 ± 0.18  | 4.55 ± 0.05   |
| NGC 0925| 0.65 [dB08]          | 16.63 ± 10.16        | 3.40 ± 0.74  | 2.09 | 22.09 ± 0.34 | 4.59 ± 0.04   |
| NGC 2366| 0.33 [dB08]          | 1.28 ± 0.11          | 37.47 ± 4.25 | 0.20 | 2.11 ± 0.04  | 0.39 ± 0.01   |
| NGC 2403| 0.74 [dB08]          | 4.53 ± 0.15          | 20.97 ± 1.02 | 0.63 | 4.74 ± 1.51  | 2.72 ± 0.03   |
| NGC 2841| 0.74 [dB08]          | 0.84                 | 50.02 ± 3.61 | 0.82 | 4.69 ± 1.72  | 0.96 ± 0.03   |
| NGC 3031| 0.80 [dB08]          | 1.00                 | 14.55 ± 5.87 | 3.97 | 4.77 ± 1.24  | 4.52 ± 0.09   |
| NGC 3109| 0.70 [Tw]            | 2.22 ± 0.20          | 25.71 ± 3.21 | 0.25 | 21.24 ± 1.91 | 1.94 ± 0.14   |
| NGC 3198| 0.80 [dB08]          | 4.85 ± 0.42          | 15.01 ± 2.15 | 1.17 | 24.26 ± 0.67 | 1.84 ± 0.02   |
| NGC 3621| 0.59 [dB08]          | 5.56 ± 0.23          | 14.31 ± 0.16 | 0.70 | 1.56 ± 0.98  | 1.52 ± 0.02   |
| NGC 7331| 0.83 [dB08]          | 1.00                 | 17.38 ± 2.75 | 4.75 ± 0.60 | 0.45  | 0.68 ± 1.08  | 0.42 ± 0.03   |
| NGC 7793| 0.31 [dB08]          | 1.90 ± 0.20          | 77.95 ± 11.13 | 3.06 | 12.58 ± 2.01 | 4.63 ± 0.13   |

\(a_0\) the I-band surface brightness profile was adopted for NGC 3109 because it has larger radial extent than the 3.6 microns surface brightness profile.

col. 1: Galaxy name; col. 2 & 3: mass-to-light ratio [reference: dB08: de Blok et al. (2008); Tw: this work; W11: Westmeier et al. (2011)]; col. 4: ISO halo core radius; col. 5: ISO halo central density; col. 6: ISO reduced chi-squared. col. 7 & 9: reduced chi-squared for \(a_0\) fixed and free; col. 8: MOND acceleration parameter

\[
\log(a_0) = (-0.055 \pm 0.037) \times \mu_{3.6} + (4.520 \pm 0.687) \tag{12}
\]

This surely challenges the universality of MOND, since \(a_0\) should be the same for every galaxy.

### 5.4 Dark Matter Halo Scaling Laws

The most common hypothesis to explain the flatness of galaxies’ RCs is to postulate the existence of a dark matter halo. The halo is characterized by a theoretical density profile. It has been known that the observational motivated ISO halo provides a better description of the observed RCs as compared to the cosmological motivated NFW halo (see e.g. de Blok et al. 2001). The success of the ISO halo for fitting galaxy RCs has been said to be due to the number of parameters involved in the fitting procedure. These parameters are the halo core radius \(R_C\) and the halo central density \(\rho_0\).

A correlation between these two parameters have been investigated in the literature (Kormendy & Freeman 2004; Barnes et al. 2004; Spano et al. 2008). Kormendy & Freeman (2004) found the following relation:

Figure 2. MOND parameter as a function of the corrected central surface brightness of the stellar disk in the 3.6 micron band.
Table 3. Effect of varying the adopted distance within the uncertainties (M/L fixed (Diet-Salpeter IMF, $a_o = 1.21 \times 10^{-8}$ cm s$^{-2}$ and using the simple interpolating function).

| Name     | (M/L)$_{3.6, disk}$ | (M/L)$_{3.6, bulge}$ | Distance Mpc | $\chi^2$ |
|----------|---------------------|----------------------|--------------|---------|
| DD0 154  | 0.32                |                      | 4.30, 3.76, 3.23 | 6.32, 3.21, 1.21 |
| IC 2574  | 0.44                |                      | 4.02, 3.61    | 19.28, 14.84 |
| NGC 0247 | 0.36                |                      | 3.41, 3.58    | 6.06, 4.96 |
| NGC 0300 | 0.27                |                      | 1.99, 1.96    | 5.43, 4.55 |
| NGC 0925 | 0.65                |                      | 9.16, 8.53    | 22.09, 18.48 |
| NGC 2403 | 0.74                |                      | 3.22, 3.36    | 4.74, 4.06 |
|           | 3.47 [G11]          |                      | 3.36         | 6.00 |
| NGC 2841 | 0.74                | 0.84                 | 14.10, 15.60  | 4.69, 2.13 |
| NGC 3198 | 0.80                |                      | 13.80, 12.95  | 24.26, 17.43 |
| NGC 7793 | 0.31                |                      | 3.43, 3.53    | 12.58, 10.88 |
|           | 3.91 [G11]          |                      | 4.30         | 6.89 |

col. 1: Galaxy name; col. 2 & 3: mass-to-light ratio; col. 4: adopted distances, G11: distance used by Gentile et al. (2011) (see text for more explanation); col. 5: reduced chi-squared;

\[
\log \rho_0 = -1.04 \times \log R_C - 1.02 \quad (13)
\]

while Spano et al. (2008) found:

\[
\log \rho_0 = -0.93 \times \log R_C - 0.74 \quad (14)
\]

A similar analysis is undertaken for our sample. A plot of the core radius as a function of the central densities is shown on the top panel of Fig. [3]. We found that our result is consistent with those
presented in the literature. This confirms the existence of a scaling relation for the central core of the dark matter halos. The following relationship was found using a simple least square method:

$$\log \rho_0 = (-1.10 \pm 0.13) \times \log R_C - (1.05 \pm 0.25)$$

(15)

The core radius is plotted as a function of absolute magnitude in Figure 3. A clear correlation is seen between these two parameters: low-luminosity galaxies correspond to a small core radius.

As shown in Figure 4, our least square fit results are:

$$\log \rho_0 = (0.121 \pm 0.021) \times M_B + (1.531 \pm 0.120)$$

(16)

$$\log r_c = (-0.133 \pm 0.044) \times M_B - (1.76 \pm 0.797)$$

(17)

The least square result found by Spano et al. (2008) were:

$$\log \rho_0 = 0.142 \times M_B + 1.29$$

(18)

$$\log r_c = -0.167 \times M_B - 2.47$$

(19)

and the results by Kormendy & Freeman (2004) were:

$$\log \rho_0 = 0.113 \times M_B + 0.12$$

(20)

$$\log r_c = -0.127 \times M_B - 1.42$$

(21)

The correlation between the central density and the absolute magnitude was also investigated which is shown in bottom panel of Fig. 3. This is in good agreement with Kormendy & Freeman (2004).

The halo surface density is given by the product of the core radius and the central density of the halo. Kormendy & Freeman (2004) found that the surface density of the halo is nearly constant as a function of absolute magnitude. This result was confirmed by Spano et al. (2008) which is shown as a green dashed line in figure 3. We found a correlation which is in good agreement with those found in the literature.

Kormendy & Freeman (2004):

$$\rho_0 R_C \sim 100 \; M_\odot \; pc^{-2}$$

(22)

Spano et al. (2008):

$$\rho_0 R_C \sim 150 \; M_\odot \; pc^{-2}$$

(23)

This work:

$$\rho_0 R_C \sim 120 \; M_\odot \; pc^{-2}$$

(24)

These results confirm the scaling laws for dark matter halos, which is important for our understanding of the relation between the dark and luminous matter and the characteristics of the dark matter itself. It clearly confirms that low luminosity galaxies have smaller core radii and higher central densities. Most importantly, it mainly implies that dark matter ISO halo could be characterized by only one parameter since the core radius and the central density of the halo are correlated. With the (M/L) of the disk now fixed by population synthesis models, DM models are thus left with only one free parameter the DM surface density.
6 CONCLUSIONS

We have presented mass models of fifteen (15) dwarf and spiral galaxies selected from the literature. Their observed RCs were confronted with MOND and the observationally motivated ISO dark matter halo model. The galaxies in the sample were selected to be homogenous in terms of their measured distances, the sampling of their RCs and the stellar M/L of the stellar contributions. The selected galaxies in the sample also cover a larger range of luminosities and morphological types than previous studies.

The models were carried out using the GIPSY software tasks ROTMOD and ROTMAS. MOND fits with $a_0$ fixed and free were performed. MOND fits with $a_0$ free were needed to re-estimate the average value of $a_0$, to identify galaxies in which $a_0$ exhibits a significant departure from the standard value of $a_0 = 1.21 \times 10^{-8}$ cm s$^{-2}$ and to look for any trend between $a_0$ and the other parameters of the galaxy. The MOND fit results are:

- An average value of $(1.13 \pm 0.50) \times 10^{-8}$ cm s$^{-2}$ was measured for the MOND acceleration constant $a_0$ which is smaller compared to the standard value of $1.21 \times 10^{-8}$ cm s$^{-2}$ found by Begeman et al. (1991) and should be considered as the standard value since our sample covers a broader range of luminosities and morphological types.
- The RCs predicted by MOND tend to be in good agreement with the observed RCs of bright spirals.
- The difference between the RCs predicted by MOND and the observed RCs is the largest for the following galaxies: DDO 154, IC 2574, NGC 925, NGC 3109, NGC 3198 and NGC 7793 which, with the exception of NGC 3198, tend to be low mass systems.
- A correlation between $a_0$ and the extrapolated disk central surface brightness is found. We found that galaxies with higher surface brightnesses require higher values of $a_0$ and galaxies with lower surface brightness prefer lower $a_0$. This is problematic for MOND as a new law of physics since $a_0$ should be a constant independent of any galaxy property.

Finally, for the mass models with dark matter halos, the ISO halo provides the best fits to the RCs ($\chi^2 = 1.18$) compared to MOND with $a_0$ fixed ($\chi^2 = 9.20$) or $a_0$ free to vary ($\chi^2 = 2.37$). The existence of the scaling relations for the central core of the dark matter halos were investigated for the ISO halo model. A correlation between the central density $\rho_0$ and the core radius $R_c$ was confirmed. This correlation implies that the dark matter halo model could be characterized by only one of the two parameters.

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NOTES ON INDIVIDUAL GALAXIES

DDO 154

DDO 154 is a gas dominated nearby dwarf galaxy, classified as an Irregular Barred galaxy or IB(s). A distance of 4.3 Mpc derived from the brightest blue stars by [Karachentsev et al. 2004] is adopted for this study. This is consistent with the previous results adopted in the literature [Carignan & Beaulieu 1989, Carignan & Freeman 1988]. The first HI observation of this galaxy was done in November 1985 (Carignan & Freeman 1988). DDO 154 is part of the THINGS sample which consists of 34 dwarf and spiral galaxies. The kinematics and RCs of 19 galaxies from the THINGS were derived by [de Blok et al. 2008] and these are the highest quality RCs available to date. The inclination and position angle are shown in Table 1. This galaxy has been studied extensively in the context of MOND. The mass model results are shown in the first row of Fig. 1, the left panel is the model with a DM halo, the right panel is an Irregular Barred galaxy or IB(s). A distance of 4.3 Mpc derived from the brightest blue stars by [Karachentsev et al. 2004] is adopted for this study. This is consistent with the previous results adopted in the literature [Carignan & Beaulieu 1989, Carignan & Freeman 1988]. The first HI observation of this galaxy was done in November 1985 (Carignan & Freeman 1988). DDO 154 is part of the THINGS sample which consists of 34 dwarf and spiral galaxies. The kinematics and RCs of 19 galaxies from the THINGS were derived by [de Blok et al. 2008] and these are the highest quality RCs available to date. The inclination and position angle are shown in Table 1. This galaxy has been studied extensively in the context of MOND. The mass model results are shown in the first row of Fig. 1, the left panel is the model with a DM halo, the middle panel is the MOND model with $a_0$ fixed and the right panel for $a_0$ free. [Milgrom & Braun 1989] consider DDO 154 as "an acute test for MOND" because its internal acceleration is deeply in the MOND regime. The poor MOND fit for DDO 154 has been interpreted as being due to the uncertainties on the measured distance since no measured Cepheid based distance is available. The uncertainties on the inclination is also known to be one of the source of the poor quality MOND fit for DDO 154 due to the unknown thickness of the HI disk. Recently, [Angus et al. 2012] used a new N-body code which solves the modified Poisson’s equation and fits galaxy RCs. They performed four parameters (M/L, stellar & gas disk scale heights and distance) MOND fits for five galaxies from THINGS. They found that an acceptable MOND fit could be obtained for DDO 154 when the gas disk scale height is taken as $z_g = 1.5$ kpc and with a larger (M/L). In our study, a good MOND fit is found for a small value of $a_0 = 0.68 \pm 0.02$, nearly half the standard value.

NGC 55

NGC 55 is a barred spiral SB(s)m galaxy member of the Sculptor group. A cepheid distance of 1.9 Mpc was measured by [Gieren et al. 2008] as part the Araucaria Project. The HI RCs was derived by Puche & Carignan (1991) from VLA observations. MOND produces an acceptable fit for the RC of this galaxy.

NGC 247

NGC 247 is a nearby dwarf galaxy part of the Sculptor group. This galaxy is classified as SB(s)cd. The most recent cepheid distance for NGC 247 is 3.4 Mpc. This was measured as part of the Araucaria Project [Gieren et al. 2008]. The RC of NGC 247 was taken from [Puche & Carignan 1991]. MOND underestimate the rotation velocities in the inner parts of the RCs which leads to a high reduced chi-squared value for this galaxy.

NGC 300

NGC 300 is a well known spiral galaxy part of the Sculptor Group classified as SA(s)d. This galaxy has been observed at 21 cm wavelength using the 27.4 m twin-element interferometer of the Owen Valley Radio Observatory [Rogstad et al. 1979] and using the Very large Array with the D and C configuration [Puche & Carignan 1991]. The HI RC in [Westmeier et al. 2011] derived from HI observations using the Australian Compact Array telescope is chosen for this analysis because of its large radial extend compared to the one derived by [Puche & Carignan 1991] derived from VLA data. This is one of the galaxies that MOND could not produce acceptable fit to the observed RCs with a reduced chi-squared of 5.43.

IC 2574 and NGC 925

[Gentile et al. 2011] mentioned the presence of holes and shells in the HI gas distribution of these two galaxies. The existence of large non-circular motions have also been noticed by [Oh et al. 2008]. Therefore, the poor quality MOND fits for these two galaxies could not be interpreted as a failure for MOND. However, the RCs we used were derived using the bulk velocity field only [Oh et al. 2008], which takes out most of the effects of local non-circular motions. This is well explained in [de Blok et al. 2008]. However, the presence of a small bar could also introduce large scale distortion in the inner parts, but this is beyond the scope of this work and will therefore be investigated in an upcoming paper using numerical simulation.

NGC 2366

NGC 2366 is a dwarf galaxy member of the M81 group. The RCs derived by [Oh et al. 2008] using the bulk velocity field is adopted for this study. MOND produces an acceptable fit to the observed RC of this galaxy.
NGC 2403

This galaxy belongs also to the M81 group of galaxies. It is classified as a barred spiral galaxy SAB(s)cd. NGC 2403 is a well known bright spiral galaxy. It has been extensively used to test MOND. For example NGC 2403 was part of the sample of Begeman et al. (1991) to estimate the value of the MOND acceleration parameter. The most recent RC of NGC 2403 was derived by de Blok et al. (2008). NGC 2403 is also part of the sample of Gentile et al. (2011) in the context of MOND. A cepheid distance of 3.22 Mpc is adopted for this work (Freedman et al. 2001). A better fit is obtained with a distance of 3.76 Mpc (see Table 3).

NGC 2841

NGC 2841 is a bright spiral galaxy in the constellation of Ursa Major. Many authors have noticed that MOND cannot reproduce the observed RC of NGC 2841 (eg. Begeman et al. 1991). Sanders Major. Many authors have shown that MOND cannot predict the RC of this galaxy with the standard value of $a_0$, unless adjustment is made on the adopted distance. A much lower distance of 8.6 Mpc is needed to reconcile MOND with the observed RC of NGC 2841 (see: Bottema et al. 2002, Gentile et al. 2011). This is much smaller than the Cepheid distance of 13.8 Mpc, adopted for our study and therefore very unlikely. Despite the non-circular motion induced by the presence of a bar, we can get reasonable DM fits but the discrepancy between the observed RC and the MOND fit is large with a $\chi^2_0 = 24.26$. MOND overestimates the rotational velocity in the outer parts, which implies more mass. A good MOND fit is only obtained by letting $a_0$ free to vary (see also: Gentile et al. 2011).

Recently, Gentile et al. (2013) derived a new RC for NGC 3198 as part of the HALOGAS (Westerbork Hydrogen Accretion in LOcal GAxieS) survey (Heald et al. 2011), which aims to study extra-planar gas in the local universe. Their new RC has a larger extent compared to the THINGS RC but with fewer data points in the inner parts. They performed MOND fits by letting the distance free to vary within the uncertainties. They found that MOND can produce a better fit in the outer parts with the new RC but the quality of the fit is much worse compared with those in the literature in the inner parts (e.g: Gentile et al. 2011, Bottema et al. 2002, Begeman et al. 1991). The inner parts of the galaxy contain most of the mass and plays an important role in the mass model. However, it is not well constrained with the new RC because of the lack of spatial resolution. Using our adopted distance, our results suggest that an acceptable MOND fits is only possible if the MOND acceleration constant $a_0$ is of about 0.67 x $10^{-8}$ cm s$^{-2}$, which is about half the standard value.

NGC 3031

NGC 3031 or M81 is a bright spiral galaxy in the constellation of Ursa Major. NGC 3031 is located at a distance of 3.63 Mpc (Freedman et al. 2001). The existence of non-circular motions is reported by de Blok et al. (2008). For this reason it is excluded from the Gentile et al. (2011) sample and the observed RC has not yet been confronted with the MOND formalism (Trachternach et al. 2008) quantified the non-circular motions for this galaxy and found that they lie between 3 and 15 km s$^{-1}$ for an average of 9 km/s. They also noticed that the outer disk is warped and that there is some disturbance in the velocity field. Allowing $a_0$ to vary did not improve the quality of the MOND fit.

NGC 3109

NGC 3109 is a nearby SB(s)m dwarf galaxy located at a distance of about 1.30 Mpc from us. The first cepheid distance of NGC 3109 was measured by Gieren et al. (2005) from a total of 19 cepheid variables. The first HI RC for this galaxy was derived by Roblin & Carignan (1990) from a VLA observation using C and D configurations. Another HI observation were done using the 64 m Parkes telescope in Australia (Barnes & de Blok 2001), but they could not derive the RC because of the lack of spatial resolution. Begeman et al. (1991) noticed that the gas component need to be increased by a factor of 1.67 after a comparison with single dish observations in the 21 cm wavelength to be in accord with MOND. Recently, Carignan et al. (2013) obtained new HI observations with the Karoo Array Telescope (KAT 7) (SKA and MeerKAT precursor) in the Karoo desert in South Africa. Since the short baselines and the low system temperature make the telescope very sensitive to large scale low surface brightness emission, all the HI gas is detected by KAT-7. Despite having now the proper gas profile, they conclude that NGC 3109 continues to be problematic for MOND. Since it has the proper gas profile, the RC derived by Carignan et al. (2013) is used in this study. NGC 3109 still exhibits a large discrepancy between the RC predicted by MOND and the observed RC. This disagreement between the MOND RC and the observed RC remained even when $a_0$ is taken as a free parameter.

NGC 3198

This is a grand design spiral galaxy in the constellation of Ursa Major. The cepheid distance of 13.80 Mpc of Freedman et al. (2001) is used in this work. NGC 3198 is a well studied galaxy in the context of MOND. Many authors have shown that MOND cannot predict the RC of this galaxy with the standard value of $a_0$, unless adjustment is made on the adopted distance. A much lower distance of 8.6 Mpc is needed to reconcile MOND with the observed RC of NGC 3198 (see: Bottema et al. 2002, Gentile et al. 2011). This is much smaller than the Cepheid distance of 13.8 Mpc, adopted for our study and therefore very unlikely. Despite the non-circular motion induced by the presence of a bar, we can get reasonable DM fits but the discrepancy between the observed RC and the MOND fit is large with a $\chi^2_0 = 24.26$. MOND overestimates the rotational velocity in the outer parts, which implies more mass. A good MOND fit is only obtained by letting $a_0$ free to vary (see also: Gentile et al. 2011).

NGC 3621

NGC 3621 is classified as SA(s)d galaxy. It is located at a distance of 6.64 Mpc in the constellation of Hydra (Freedman et al. 2001). It is a well behaved galaxy with a flat RC up to very large radii. Both MOND and dark matter models produce good fits to the observed RC.

NGC 7331

NGC 7331 is a spiral galaxy in the constellation of Pegasus classified as SA(s)b galaxy. A cepheid distance of 14.72 Mpc (Freedman et al. 2001) is adopted in this study. The HI RC of NGC 7331 have been confronted to MOND by Begeman et al. (1991) using VLA observations and Gentile et al. (2011) using data from the THINGS survey (Walter et al. 2008). Their conclusions that MOND is able to fit the observed RC is confirmed in this work.
NGC 7793

NGC 7793 is a member of the Sculptor Group classified as S(s)d. The most recent cepheid distance for NGC 7793 is 3.43 Mpc. This was measured as part of the Araucaria Project (Gieren et al. 2005). The RC derived from the THINGS data is used in this study. The quality of the MOND and dark matter fits are similar for this galaxy (see Gentile et al. 2011 for the MOND and de Blok et al. 2008 for the dark matter fits). This is confirmed by the chi-square values listed in Table 2 for the MOND and ISO models.

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