ACCURATE DETERMINATION OF THE MASS DISTRIBUTION IN
SPIRAL GALAXIES:
II. Testing the Shape of Dark Halos

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ABSTRACT

New high resolution CFHT Fabry–Perot data, combined with published VLA 21 cm observations are used to determine the mass distribution of NGC 3109 and IC 2574. The multi-wavelength rotation curves allow to test with confidence different dark halo functional forms from the pseudo-isothermal sphere to some popular halo distributions motivated by CDM N-body simulations. It appears that the density distributions with high central concentration, predicted by these simulations, are very hard to reconcile with rotation curves of late type spirals. Modified Newtonian Dynamics (MOND) is also considered as a potential solution to missing mass and tested the same way. Using the higher resolution Hα data, and new HI data for NGC 3109, one can see that MOND can reproduce in details the rotation curves of IC 2574 and NGC 3109. However, the value for the MOND universal constant is ∼2 times larger than the value found for more massive spirals.

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1. Introduction

Over the last 30 years, rotation curves have been a very efficient tool to study the mass distribution in spiral galaxies. They clearly brought to light the important discrepancy between the luminous mass and the gravitational mass that has led to the supposition of a large amount of dark matter in the Universe. The now commonly accepted picture is that this unseen matter takes the form of large halos in the center of which galaxies are embedded. Alternatively, the gravitational attraction could deviate from the pure Newtonian force at very low acceleration so that no dark matter is necessary.

The resolution reached by N-body simulations of the cosmic evolution of dark halos (Navarro et al. 1996b, 1997; Fukushige & Makino 1997; Moore et al. 1998; Kravtsov et al. 1998) allows one to predict the inner part of halo density profiles. In theory, these profiles could be directly compared to the ones deduced from modeling the rotation curves. Unfortunately, the sensitivity of the rotation curves to the exact density profile of the halos is quite low and one must use the highest sensitivity and the highest resolution possible to arrive at useful comparisons (Blais-Ouellette et al. 1999, hereafter paper I).

This study investigates primarily, in the context of Newtonian gravitation, the density profiles of the dark halos of two late type spiral galaxies: NGC 3109 and IC 2574. As late type, their bulge is minimal making them well suited objects for sensitive mass distribution studies because of the reduced uncertainties due to the negligible spheroid contribution in the inner parts. Mass models of NGC 3109 based on radio observations have already been presented by Jobin & Carignan (1990) while the dark matter distribution in IC 2574 has been studied by Martimbeau et al. (1994). New high resolution Fabry-Perot observations of the Hα emission line are used in combination with published 21 cm data to form accurate multi-wavelength rotation curves. These curves are used to model the mass distribution in the galaxies. The models include a stellar disk, a gaseous component and a dark spherical halo.

Moreover, NGC 3109 has often been presented as a test for the Modified Newtonian Dynamics (Milgrom 1983). As noted in Broeils (1992), the inner part of the rotation curve is crucial to draw any conclusion on the MOND fit to this galaxy. Therefore, the mass models of the two galaxies based on the MOND assumption are presented as well.

The CFHT Fabry-Perot observations are described in Section 2 while the mass models of the two galaxies, to which we add NGC 5585 and NGC 3198 from paper I, are discussed in Section 3.
2. New Fabry–Perot Observations

The Fabry-Perot observations of the Hα emission line were obtained in February 1994 at the Canada–France–Hawaii Telescope (CFHT). The etalon (CFHT1) was installed in the CFHT’s Multi–Object Spectrograph (MOS). A narrow–band filter (∆λ ≈ 12 Å), centered at λ_0 = 6565.5 Å for NGC 3109 (V_{sys} ≈ 402 km s\(^{-1}\)) and at λ_0 = 6559.5 Å for IC 2574 (V_{sys} ≈ 53 km s\(^{-1}\)) , was placed in front of the etalon. The available field with no vignetting was ≈ 8.5′ × 8.5′, with 0.314′′ px\(^{-1}\). The pixel were binned 3 by 3 to increase the signal-to-noise ratio and minimize the readout time. The free spectral range of 5.66 Å (259 km s\(^{-1}\)) was scanned in 27 (plus one overlapping) channels, giving a sampling of 0.21 Å (9.6 km s\(^{-1}\)) per channel. Eight minutes integration were spent at each channel position. Table 1 lists the complete observing parameters.

Following normal de–biasing and flat–fielding with standard IRAF procedures, a robust 3-D cosmic–ray removal routine, that tracks cosmic rays by spatial (pixel–to–pixel) and spectral (frame–to–frame) analysis, was applied. Ghost reflections were then removed using the technique described in Paper I. With the ADHOC software package\(^c\), photometric variations were corrected using the mean night sky (background + emission lines) to calculate the corrections to apply to each frame. Then, a calibration based on a neon lamp (λ6598.95 Å) was used to fix the zero point of the spectrum at each pixel.

2.1. NGC 3109

Table 2 gives the optical parameters of NGC 3109. In order to get sufficient signal–to–noise throughout the velocity fields, two different Gaussian spatial smoothings (σ=3.5 and 5 pixels) were performed on the cube (all the channels). Velocity maps were then obtained from the intensity weighted means of the Hα peaks to determine the radial velocity for each pixel. A final variable resolution velocity map (Fig. 1, top) was built keeping higher resolution for regions with originally higher signal-to-noise. The full resolution Hα image is also shown on the lower part of Fig. 1.

The rotation curve was obtained from the velocity field using two different methods. First, an estimate was made using the task ROCUR (Begeman 1987; Côté et al. 1991) in the AIPS package, where annuli, tilted with respect to the plane of the galaxy (ellipses in the plane of sky), are fitted to the velocity field, minimizing the dispersion inside each annulus. The dynamical center, systemic velocity, position angle and inclination were estimated this way. Secondly, the ADHOC package was used to fine–tune these parameters by comparison of both sides of the galaxy and examination of the residual velocity field (see Amram et al. 1992, for the detailed method). The systemic velocity was found to be 402 km s\(^{-1}\), very close to the value of 404 km s\(^{-1}\) found with the HI observations of Jobin & Carignan (1990). Since a warp is clearly present even in the optical velocity field, the

\(^c\)http://www-obs.cnrs-mrs.fr/adhoc/adhoc.html
final rotation curve was derived with ROCUR leaving the inclination and the position angle free to vary. In this context, the slightly high value of the first velocity point can be understood as a product of the poor determination of the inclination in the center of the galaxy. Table 3 gives the full rotation curve at 20" resolution, while Fig. 2 illustrates the rotation curve as well as the variation of inclination and position angle. Following Jobin & Carignan (1990), the rotation curve was corrected for asymmetric drift.

Currently, no convention on the way to represent the errors on rotation curves exists in the literature. Error bars are often simply given as the velocity dispersion in the ring used at each radius. However, warm gas is known to be more sensitive to its environment than cold gas. Turbulence, local density variations (like spiral arms, bars, etc.) and winds from stars and supernovae of the young stellar forming regions in which the ionized gas is found, increase its dispersion. This can lead to the paradox that the fewer points you have (as in long–slit observations) the lower is your dispersion and the smaller are your error bars. As a more direct probe of the uncertainties on the measured potential, the difference between the two sides of the galaxy is instead often used. Some authors will add the error due to uncertainties on inclination and/or position angles.

To differentiate clearly the source of errors, the error bars shown here indicate the error on the mean in each ring ($\sigma/\sqrt{N}$) while the solutions for each side of the galaxy are represented by lines (continuous for the receding side and dashed for the approaching). Their difference is a good estimate of the asymmetry and large scale non–circular motions.

The velocity field of NGC 3109 shows many bubble–like features probably due to intense star formation especially close to the center of the galaxy. The effect of Hα bubbles are normally of two kinds: first, if the front and back sides of a bubble are equally intense and the medium transparent, a broadened or even, depending on the resolution, a doubled Hα line can be seen. The true gravitational rotation can still be deduced by averaging the two peaks. However, in many cases only the front side of an expanding bubble can be seen, making it difficult to retrieve the true rotational velocities.

In the case of NGC 3109, analysis of the velocity field shows a small deviation from circular motion in the inner part of the galaxy. The velocity of the single innermost point of the rotation curve is slightly affected. Despite some internal peculiar velocities, apparently well averaged out, a relatively good agreement can be seen between the two sets of data. The HI velocities (where no beam smearing correction has been applied) were just slightly underestimated in the inner part. This is not really surprising considering that beam smearing effects should diminish as the slope of the inner rotation curve diminishes for a given beam width. The multi–wavelength rotation curve is thus composed of the Hα data points up to 410 ° and of HI velocities for the rest.
2.2. IC 2574

A similar reduction procedure was applied to IC 2574 (Table 4) and the velocity field is shown juxtaposed to the monochromatic image in Fig. 3. It is clear that IC 2574 is more disrupted than NGC 3109. With such a patchy velocity field, a determination of a reliable rotation curve with an iterative method based on velocity dispersion in annuli turned out to be impossible. Direct calculation of the rotation velocity for each pixel was thus done using fixed values for the position angle and the inclination. The dynamical parameters were found by comparing the two sides of the galaxy and by analyzing the residual field. The resulting rotation curve is presented in Table 5 based on a systemic velocity of 53 km s\(^{-1}\), a position angle of 52° and an inclination of 75°, almost identical to the parameters found by Martimbeau et al. (1994) from the HI observations.

The H\(\alpha\) rotation curve (Fig. 4) follows more or less the same kind of perturbations as those seen in the HI curve. For example, when one compares the two sides of the HI curve in the Fig. 8 of Martimbeau et al. (1994): (i) the effect of a giant bubble can clearly be seen at both wavelengths around 240" on the approaching side; (ii) the giant north–eastern OB association clearly shows up between 7' and 10' of the receding side; (iii) on the other hand, some probable non-circular motions are seen around 100" in the H\(\alpha\) but do not show up in the HI.

Since the comparison of HI and H\(\alpha\) data shows no sign of beam smearing, there would be no reason here to use the disrupted H\(\alpha\) curve instead of the 21 cm data as the probe of the gravitational potential of the galaxy.

3. Mass Models and Parameters of the Mass Distribution

3.1. Comparison of different models using standard gravity

The method used in this paper to model the mass distribution is a slight generalization of the one described in Carignan & Freeman (1985). The luminosity profile, if possible in the near infrared to probe the mass dominant stellar component, is transformed into a mass distribution for the stellar disk, assuming a variable but radially constant mass–to–light ratio ((\(M/L_B\))\(\star\)) (Casertano 1983; Carignan & Freeman 1985). For the contribution of the gaseous component, the HI radial profile is used, scaled by 1.33 to account for He. The difference between the observed rotation curve and the contribution to the curve from the luminous (stars & gas) component is thus the contribution of the dark component, which can be represented by a dark spherical halo. There are therefore three free parameters, the \((M/L_B)\)\(\star\) for the disk, and two parameters for the dark halo: the central density \(\rho_0\) and the core radius \(r_c\). A best fit routine minimizes the \(\chi^2\) in the three dimension parameter space.

Many studies approximate later type spirals such as NGC 3109 and IC 2574 as being totally made of dark matter, neglecting the stellar and gaseous components. This is a good approximation down to a certain radius. However, the innermost parts of the rotation curves are crucial to test
the shape of the density profiles. Best fit models that include the contributions of gas and stars are therefore used to avoid an overestimation of the dark halo contribution.

Following Kravtsov et al. (1998, hereafter KKBP) and Zhao (1996), we use an even broader family of density profiles for the halo:

$$\rho(r) = \frac{\rho_0}{(c + (r/r_0)^\gamma)(1 + (r/r_0)^\alpha)^{(\beta-\gamma)/\alpha}}$$

where $\rho_0$ and $r_0$ are a characteristic density and radius respectively, and $c$ can force the presence of a flat density core. The parameters $\alpha$, $\beta$ and $\gamma$ determine the shape of the density profile.

One can either fit the value of $(c, \alpha, \beta, \gamma)$ to a particular density profile or set them to a desired value: $(1, 0, 2, 2)$ for a pseudo-isothermal sphere (Begeman 1987); $(0, 1, 3, 1)$ for a NFW type halo (Navarro et al. 1996b); $(1, 2, 3, 1)$ for halos with flat density cores proposed by Burkert (1995) or $(0, 2, 3, 0.2)$ as proposed by KKBP. These four density profiles are presented in Fig. 5. Profiles with non-constant density cores ($\lim_{r \to 0} (\rho) \neq \rho_0$), are defined as cuspy. For these profiles, the inner slope is given by $-\gamma$, the outer slope by $\beta$ while $\alpha$ controls the sharpness of the turnover point.

NGC 3109 is particularly well suited for dynamical studies: First because its luminous component is minimal (B-band photometry from Kent 1987) so that the uncertainties related to the unknown mass-to-light ratio of the disk do not have a significant impact. Second, this galaxy is close enough to allow direct distance estimation via multicolor observations of a large number of Cepheids (Musella et al. 1997). The adopted distance is 1.36 Mpc.

In Fig. 6 and 7, best-fit models are given for the rotation curves of NGC 3109 and IC 2574, respectively. The high resolution data (used up to 410 ″ for NGC 3109) remove some uncertainties pointed out by Navarro (1997) in the differences between HI curves from different generations of radio-telescopes (single dish and aperture synthesis). It confirms the great difficulty of reconciling a cuspy profile with $\gamma \geq 1$ and the rotation curve of a late type spiral like NGC 3109. Either constant density core profiles or mildly cuspy profiles with $\gamma \ll 1$ can fit the data adequately. It is very difficult to discriminate between a density distribution with a flat core from one with a mild cusp because $r_0$ can often be stretched to a point where the two types of profile match. One has to go to very small radii ($\lesssim \gamma r_0$) to really probe any incompatibility.

Cuspy profiles with $\gamma \geq 1$ seem to appear generically in cold dark matter (CDM) N-body simulations but many models have been suggested that deviate somewhat from the standard CDM assumptions and avoid the creation of a steep central density cusp. As noted by KKBP, Syer & White (1998) showed that $\gamma$ is sensitive to the past merger rate and to the power spectrum of the initial density fluctuations on the scale of a galactic halo. Therefore a less active merger history or a steeper power spectrum should lead to $\gamma < 1$ on galactic scales. Recently however (Kravtsov et al. 2000), KKBP withdrew their N-body simulation results. Thus, their density profiles used here should not be considered as a product of CDM simulations.
Self-interacting dark matter (Spergel & Steinhardt 2000) has also been suggested to suppress the formation of high density dark matter cusps but the implied inverse dependency of the core radius on the mass of the galaxy (Dalcanton & Hogan 2000) is not observed in our sample.

Alternatively, in order to explain the presence of a flat density core in dwarf spirals for standard, scale free CDM models, Navarro et al. (1996a) suggested that a violent starburst could eject the gas and consequently flatten the inner dark matter distribution. Semi-analytical calculations give this scenario the right order of magnitude for a low mass galaxy given a sufficient feedback efficiency (van den Bosch et al. 2000).

Another way to reconcile the too steep rotation curves without invoking a flat density CDM core is to add a second dark component, composed of compact objects, to the non–baryonic cold dark matter (Burkert & Silk 1997). Of course this adds some degrees of freedom when fitting rotation curves and a better fit is in this case somewhat meaningless, making this hypothesis hard to test. The present knowledge of the importance and distribution of MAssive Compact Halo Objects (MACHOs) in our own Galaxy allow them to account for around 20% (up to 50% at a 95% confidence level) of the galactic dark matter (Alcock et al. 2000). In any case, this is barely enough to solve the cusp problem. Indeed, the MACHOs would need a very finely tuned distribution.

NGC 5585 is also well fitted by all the profiles but the NFW (Fig. 8). The slight difference between the \((M/L_B)_{\star}\) found here (0.85) and the one found in paper I (0.80) is due to the use of equation 1 instead of the integration of the appropriate Lane-Emden equation for the isothermal sphere.

In the case of NGC 3198 (Fig. 9), all the profiles are compatible. The Hα curve has been used up to 65 ″ to rectify the overcorrection of the beam smearing in Begeman (1987). The only remark to be made is that all the profiles are too smooth to account for the small variations in the outer rotation curve, even though they are present in both the HI and the B profile. The detailed gravitational interplay between luminous and dark matter should be taken into account. The detailed results of the mass models can be found in Table 6.

3.2. Modified Newtonian Dynamics

Milgrom (1983) proposed that a modification of Newtonian gravitation in the low acceleration limit could mimic a large amount of dark matter in spiral galaxies. The MOdified Newtonian Dynamics (MOND) is a truly falsifiable theory: it contains only one parameter, \(a_0\), that is supposed to be a universal constraint. A lot of work has been done using rotation curves for which the quality of the data gives the best opportunity to test the theory (e.g. Begeman et al. 1991; Sanders 1996; Sanders & Verheijen 1998; McGaugh & De Blok 1998).

As a reminder, here is the MOND quantitative prescription. For purely circular motion, one
can equate the centripetal and gravitational acceleration. In the Newtonian regime, we simply get

$$\frac{V^2}{R} = \frac{GM_T}{R^2} = g_N$$

(2)

MOND states that the true force is given by

$$\mu(\frac{g}{a_0})g = g_N$$

(3)

where $\mu(\frac{g}{a_0})$ is an interpolation function that has the right asymptotic behavior: $\mu(\frac{g}{a_0} \gg 1) \rightarrow 1$ and $\mu(\frac{g}{a_0} \ll 1) \rightarrow \frac{g}{a_0}$.

The exact form of $\mu(\frac{g}{a_0})$ has no impact on the mass models of very late type spirals like NGC 3109 and IC 2574 where the gravitational acceleration is well below $a_0$ at all radii but

$$\mu(x) = \frac{x}{\sqrt{1 + x^2}}$$

(4)

is generally assumed to be the interpolation function.

In the limit of low acceleration the gravitational acceleration is thus given by $g = \sqrt{a_0 g_N}$ and

$$\frac{V^2}{R} = \sqrt{\frac{GM_T}{R^2} a_0}$$

(5)

or

$$V^4 = GM_T a_0$$

(6)

which naturally explains the asymptotic flatness of rotation curves and the Tully-Fisher relation.

A best–fit method, similar to the one used for dark halos has been applied. The stellar luminosity profile and the HI density profile are this time transformed into a mass distribution following equations (3) and (4). The free parameter of the fit is as always the $(M/L)_*\,$ ratio, $a_0$ is considered as a universal constant, but, since no fundamental theory exists as of yet to give its true value, 2 different values are used in the fits. First, the value found by Begeman et al. (1991) that best fits their highly selective and high quality sample of luminous spirals ( $1.2 \times 10^{-13}$ km s$^{-1}$).

The second value is the one that best fits each present galaxy individually (Table 7). Fig. 10 shows the best fit for each galaxy and Table 7 indicates the parameters when using the best fitted $a_0$.

IC 2574, NGC 3109 and NGC 3198 are fairly well fitted by the MOND law if the “universal constant” $a_0$ is allowed to vary by more than a factor 2. The quality of the fit is especially good in the case of IC 2574, where most of the features of the rotation curve are reproduced in the fit. On the other side, the MOND prescription has more difficulties to account for the mass distribution of NGC 5585 whatever the value of $a_0$. Being for a large part in the Newtonian regime, the case of NGC 5585 is somewhat less significant as it probes more the interpolation function than the MOND theory itself. In contrast, NGC 3109 belongs fully to the MOND regime. In this case, using new Australia Telescope Compact Array HI data improve significantly the MOND fit compared to the one obtained with the old VLA data (the $\chi^2$ going from 5 to 2), which were missing 1/3 of the flux.
4. Summary and Discussion

With the four galaxies studied so far, it is clear that while there is a good agreement between Fabry-Perot and HI data for the shallow rotation curves of the late type galaxies NGC 3109 and IC 2574, beam smearing plays an important role for the steeper rotation curves. Beam smearing thus seems to depend on at least two factors: the inner slope of the rotation curve and the sampling of the curve, often expressed as the ratio of the Holmberg radius to the beam width (Bosma 1978). Bosma suggested a ratio greater than 6 to have a reliable HI curve. This ratio is about 7 for NGC 5585 and 30 for NGC 3109 and the latter is still slightly affected by beam smearing.

Using multi-wavelength rotation curves to determine the density profiles of dark matter halos, it appears clearly that cuspy profiles with inner logarithmic slope $\gamma \geq 1$ do not match the observations. The best fits are achieved using either a slightly cuspy profile with a very shallow inner slope or a profile with a flat density core. If current simulations correctly describe CDM evolution, an additional process is needed to destroy or forbid the formation of a central cusp. However, none of the actually proposed scenarios stand out as the most plausible either because they are not easily testable or their predictions do not appear clearly in the data.

The Modified Newtonian Dynamics prescription can fit the rotation curves of IC 2574, NGC 3109 and NGC 3198 obtained from the new high resolution data if $a_0$ is free to vary by a factor of 2. In this case, most of the features of the rotation curve are even reproduced with the right amplitude. Of course, since there is almost no stellar disk, at least in the part fully in the MOND regime, scaling the HI would produce a similar result. Can $H_2$ be involved here? (Pfenniger et al. 1994). On the other hand, the variations of the stellar and gaseous components also possibly just follow a non-smooth dark matter distribution.

There is always a danger to let what should be a universal constant like $a_0$ vary to fit the data. However, since no underlying theory exists yet, it is interesting to note that for these late type spirals, $a_0$ seems systematically higher than for the earlier types.

5. Conclusion

The present work leads to the following conclusions:

- Observations of the kinematics of the ionized hydrogen in NGC 3109 and IC 2574 are in good agreement with the previous kinematical studies of atomic hydrogen. This implies that beam smearing was limited in the HI data, although NGC 3109 was slightly affected.

- Overall, beam smearing can be important even for “good sampling” depending on the inner slope of the rotation curve.

- The CDM models with a inner density slope $\gamma \geq 1$ are not compatible with the data on NGC 3109 and IC 2574. Flat density core models like the pseudo-isothermal sphere or a model with a
shallow inner density slope are compatible with the four galaxies in our sample.

- With the exception of NGC 5585, the MOND prescription can fit the rotation curves of the three other galaxies in our sample if the universal constant $a_0$ is allowed to vary by more than a factor of 2. The $a_0$ values found for the late type galaxies are systematically higher than what was found previously for more massive spirals.

The present examples give a good idea of the impact of higher resolution rotation curves. There are however large unexplored regions in terms of galaxy mass, surface brightness and morphological types. It is thus imperative to extend this sample to earlier type galaxies covering a large range in surface brightness. This would give, among other things, the opportunity to study precisely at what point the rotation curves stop agreeing with N-body simulations.

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Fig. 1.— Velocity field and Hα image of NGC 3109. North is up and East is left. The X and the grey line indicate the kinematic center and the axis of separation between the approaching and receding sides.

Fig. 2.— Top Hα rotation curve of NGC 3109 (open circles) compared to the HI rotation curve (filled circles) from Jobin & Carignan (1990). The approaching and receding sides are respectively represented by the dashed and continuous lines; bottom variation with radius of the position angle and inclination for the Hα data. See the text for details on curves and error bars.

Fig. 3.— Velocity field and Hα image of IC 2574. North is up and East is left. The X and the grey line indicate the kinematic center and the axis of separation between the approaching and receding sides.

Fig. 4.— Hα rotation curve of IC 2574 (open circles) compared to the HI rotation curve (filled circles) from Martimbeau et al. (1994). The approaching and receding sides of the Hα curve are respectively represented by the dashed and continuous lines.

Fig. 5.— Density profiles of the four models. solid: pseudo-isothermal sphere, dot: KKBP, long dash: Burkert, short dash: NFW.

Fig. 6.— Best fit mass models for NGC 3109 using the Hα rotation curve up to 2.7 kpc and the HI rotation curve for the rest. The dark halos density profiles are top–left: pseudo-isothermal sphere, top–right: KKBP, bottom–left: Burkert, bottom–right: NFW.

Fig. 7.— Mass models of IC 2574 using the HI rotation curve only.

Fig. 8.— Mass models of NGC 5585 using the Hα rotation curve up to 3.5 kpc and HI for the rest.

Fig. 9.— Mass models of NGC 3198 using the Hα rotation curve up to 2.9 kpc and HI for the rest.

Fig. 10.— Best fit mass models using MOND. Two different values of $a_0$ are used: the dotted line used $a_0 = 1.2 \times 10^{-13}$ km/s$^2$ from Begeman et al. (1991); the continuous line used the best fit value (see Table 7). The filled circles represent the data used in the fits (HI +Hα for NGC 3109 and 5585 and HI only for IC 2574 and NGC 3198). The open circles indicate the Hα velocities unused in the fits.
Table 1. Parameters of the Fabry–Perot observations.

| Parameter                                      | Details                                      |
|------------------------------------------------|----------------------------------------------|
| Dates of observations                          | February 21 and 22, 1994                     |
| Telescope                                      | 3.6 m CFHT                                   |
| Instrumentation                                |                                              |
| Focal plane instrument                         | MOSFP                                        |
| CCD detector                                   | 2048 × 2048 Loral3, $\sigma = 8 \text{ e}^{-1}$ |
| Fabry–Perot etalon                             | Scanning QW1162 (CFHT1)                     |
| Interference order                            | 1155 @ $\lambda_{\text{NEON}}$              |
| Mean Finesse in the field                      | 12                                           |
| Calibration lamp                               | Neon ($\lambda = 6598.95 \text{ Å}$)       |
| Duration                                       |                                              |
| NGC 3109 Per channel                           | 7.28 min/channel                             |
| Total                                          | 3 h 24 min                                   |
| Filter                                         | $\lambda_0 = 6565.5 \text{ Å}$, $\Delta\lambda = 12 \text{ Å}$ |
| IC 2574 Per channel                            | 8.05 min/channel                             |
| Total                                          | 3 h 45 min                                   |
| Filter                                         | $\lambda_0 = 6559.5 \text{ Å}$, $\Delta\lambda = 12 \text{ Å}$ |
| Spatial Parameters:                            |                                              |
| Field size                                     | $8.5' \times 8.5'$                           |
| Pixel scale                                    | $0.314'' \text{ pix}^{-1}$                   |
| Spectral Parameters:                           |                                              |
| Number of channels                             | 27                                           |
| Free spectral range                            | 5.66 Å (259 km s$^{-1}$)                     |
| Sampling                                       | 0.21 Å (9.6 km s$^{-1}$)/channel              |
Table 2. Parameters of NGC 3109.

| Parameter                                      | Value                                      |
|-----------------------------------------------|--------------------------------------------|
| Morphological Typea                          | SBm                                        |
| RA (J2000.0)                                  | $10^b 03^m 06.6$                           |
| Dec (J2000.0)                                 | $-26^\circ 09'32''$                       |
| l                                             | 262 $^\circ$                               |
| b                                             | 23 $^\circ$                                |
| Adopted distance (Mpc)$^b$                    | 1.36                                       |
| Mean axis ratio, $q = b/a$ $^c$                | 0.28 $\pm$ 0.02                            |
| Inclination, $i$ $^c$                         | 75 $^\circ$ $\pm$ 2 $^\circ$              |
| Isophotal major diameter, $D_{25}$ $^c$       | 14.4 $'$                                   |
| Major axis PA$^c$                             | 93 $^\circ$ $\pm$ 2$^\circ$               |
| Exponential scale length (kpc)$^c$            | 1.2                                        |
| Holmberg radius, $R_{HO}$ $^c$                | 13.3 $'$                                   |
| Absolute magnitude, $M_B$ $^c$                | $-16.35$                                   |
| Total luminosity, $L_B$                       | $5.2 \times 10^8 \ L_\odot$               |
| Helio. radial velocity (km s$^{-1}$)$^c$      | 404 $\pm$ 3                                |

$^a$De Vaucouleurs et al. (1991)

$^b$Musella et al. (1997)

$^c$Jobin & Carignan (1990)
Table 3. Optical rotation curve of NGC 3109 at 20" binning from ROCUR. The two sides and the global rotational velocities are computed independently. The later are corrected for asymmetric drift.

| $R_{sides}$ | $V_{app}$ | $V_{rec}$ | $R$ | $V$ |
|-------------|-----------|-----------|-----|-----|
| $''$ | km s$^{-1}$ | km s$^{-1}$ | km s$^{-1}$ | km s$^{-1}$ |
| 35 | 8 ± 1 | 3 ± 1 | 30 | 10 ± 2 |
| 65 | 6 ± 1 | 70 | 10 ± 1 |
| 95 | 15 ± 1 | 90 | 15 ± 1 |
| | | 110 | 15 ± 1 |
| 125 | 14 ± 1 | 130 | 15 ± 1 |
| 155 | 22 ± 2 | 150 | 20 ± 1 |
| | | 170 | 25 ± 1 |
| 185 | 25 ± 1 | 190 | 25 ± 1 |
| 215 | 26 ± 1 | 210 | 26 ± 1 |
| | | 230 | 32 ± 1 |
| 245 | 32 ± 1 | 250 | 33 ± 1 |
| 275 | 34 ± 1 | 33 ± 1 | 270 | 37 ± 2 |
| | | 290 | 35 ± 2 |
| 305 | 35 ± 1 | 32 ± 135 | 310 | 37 ± 2 |
| 335 | 39 ± 2 | 37 ± 1 | 330 | 39 ± 2 |
| | | 350 | 41 ± 4 |
| 365 | 46 ± 6 | 40 ± 8 | 370 | 49 ± 10 |
| 395 | 52 ± 9 | 42 ± 4 | 390 | 47 ± 2 |
| | | 410 | 48 ± 1 |
| 425 | 46 ± 2 | 45 ± 11 |

Note. — derived with $V_{sys} = 402$ km s$^{-1}$ (see text)
Table 4. Optical parameters of IC 2574.

| Parameter                                      | Value                        |
|-----------------------------------------------|------------------------------|
| Morphological Type                           | SABm                         |
| RA (J2000.0)                                  | 10^h 28^m 21.2^s            |
| Dec (J2000.0)                                 | 68°24'43''                   |
| l                                             | 140.2                        |
| b                                             | 43°6                         |
| Adopted distance (Mpc)^b                       | 3.0                          |
| (1' ≃ 0.8 kpc)                                |                              |
| Mean axis ratio, q = b/a^b                     | 0.48 ±0.06                   |
| Inclination, i^b                              | 75°±3°                       |
| Isophotal major diameter, D_25^b               | 9.8'                         |
| Major axis PA^b                               | 52°±6°                       |
| Exponential scale length (kpc)^b               | 2.2                          |
| Holmberg radius, R_HO^b                       | 8.6'                         |
| Absolute magnitude, M_B^b                     | -16.77                       |
| Total luminosity, L_B                         | 8.0 × 10^8 L_☉              |
| Helio. radial velocity (km s^{-1})^b          | 58 ±3                        |

^aDe Vaucouleurs et al. (1991)

^bMartimbeau et al. (1994)
Table 5. Optical rotation curve of IC 2574 at 9.4\arcsec binning from ADHOC. The two sides are computed independently and the total is their mean averaged by the number of points. The velocity dispersion and the number of points appear for both sides while the error is the $\sigma/\sqrt{N}$ of the sides, added in quadrature.

| $R$ arcsec | $N_{app}$ | $V_{app}$ km s$^{-1}$ | $\sigma_{ring}$ km s$^{-1}$ | $N_{rec}$ | $V_{rec}$ km s$^{-1}$ | $\sigma_{ring}$ km s$^{-1}$ | $V$ km s$^{-1}$ |
|------------|-----------|------------------------|-----------------------------|-----------|------------------------|-----------------------------|-----------|
| 8          | 2         | 22                     | 8                           | 22        | 5                      | 22 ± 5                      | 22 ± 5    |
| 12         | 3         | 34                     | 9                           | 34        | 5                      | 34 ± 5                      | 34 ± 5    |
| 15         | 22        | 8                      | 20                          | 8         | 4                      | 8 ± 4                       | 8 ± 4     |
| 24         | 36        | 15                     | 10                          | 7         | 11                    | 7 ± 1                       | 7 ± 1     |
| 33         | 26        | 12                     | 21                          | 3         | 27                    | 3 ± 2                       | 3 ± 2     |
| 43         | 22        | 2                      | 20                          | 2         | 2                     | 2 ± 2                       | 2 ± 2     |
| 52         | 62        | 10                     | 15                          | 3         | 22                    | 3 ± 2                       | 3 ± 2     |
| 61         | 101       | 17                     | 22                          | 6         | 17                    | 6 ± 2                       | 6 ± 2     |
| 70         | 139       | 27                     | 24                          | 9         | 16                    | 9 ± 1                       | 9 ± 1     |
| 80         | 151       | 30                     | 29                          | 14        | 21                    | 14 ± 2                      | 14 ± 2    |
| 89         | 113       | 42                     | 37                          | 16        | 25                    | 16 ± 2                      | 16 ± 2    |
| 99         | 62        | 43                     | 23                          | 29        | 33                    | 29 ± 2                      | 29 ± 2    |
| 108        | 75        | 33                     | 23                          | 157       | 16                    | 16 ± 2                      | 16 ± 2    |
| 118        | 78        | 31                     | 25                          | 144       | 20                    | 20 ± 2                      | 20 ± 2    |
| 127        | 72        | 33                     | 27                          | 137       | 19                    | 19 ± 2                      | 19 ± 2    |
| 137        | 53        | 53                     | 28                          | 206       | 12                    | 12 ± 2                      | 12 ± 2    |
| 146        | 40        | 66                     | 26                          | 423       | 9                     | 9 ± 1                       | 9 ± 1     |
| 155        | 41        | 79                     | 33                          | 646       | 8                     | 8 ± 1                       | 8 ± 1     |
| 165        | 45        | 54                     | 40                          | 739       | 13                    | 13 ± 2                      | 13 ± 2    |
| 174        | 68        | 37                     | 46                          | 734       | 11                    | 11 ± 2                      | 11 ± 2    |
| 183        | 81        | 25                     | 18                          | 712       | 10                    | 10 ± 1                      | 10 ± 1    |
| 193        | 94        | 30                     | 15                          | 593       | 6                     | 6 ± 1                       | 6 ± 1     |
| 202        | 102       | 31                     | 22                          | 510       | 8                     | 8 ± 1                       | 8 ± 1     |
| 212        | 141       | 32                     | 29                          | 457       | 12                    | 12 ± 1                      | 12 ± 1    |
| 221        | 193       | 34                     | 24                          | 410       | 13                    | 13 ± 1                      | 13 ± 1    |
| 230        | 155       | 30                     | 22                          | 309       | 16                    | 16 ± 1                      | 16 ± 1    |
| 240        | 147       | 42                     | 34                          | 418       | 12                    | 12 ± 2                      | 12 ± 2    |
| 249        | 139       | 42                     | 34                          | 487       | 14                    | 14 ± 2                      | 14 ± 2    |
| 259        | 185       | 43                     | 28                          | 497       | 15                    | 15 ± 1                      | 15 ± 1    |
| 268        | 190       | 40                     | 21                          | 372       | 12                    | 12 ± 1                      | 12 ± 1    |
| 278        | 138       | 44                     | 23                          | 234       | 21                    | 21 ± 2                      | 21 ± 2    |
| 287        | 245       | 39                     | 20                          | 262       | 19                    | 19 ± 1                      | 19 ± 1    |
| 296        | 287       | 44                     | 13                          | 258       | 28                    | 28 ± 1                      | 28 ± 1    |
| 306        | 289       | 42                     | 10                          | 279       | 24                    | 24 ± 1                      | 24 ± 1    |
| 314        | 279       | 38                     | 11                          | 218       | 23                    | 23 ± 1                      | 23 ± 1    |
| 325        | 188       | 36                     | 20                          | 172       | 24                    | 24 ± 2                      | 24 ± 2    |
| 334        | 347       | 37                     | 20                          | 195       | 31                    | 31 ± 2                      | 31 ± 2    |
| R (arcsec) | N\(_{\text{app}}\) | V\(_{\text{app}}\) (km s\(^{-1}\)) | \(\sigma_{\text{ring}}\) (km s\(^{-1}\)) | N\(_{\text{rec}}\) | V\(_{\text{rec}}\) (km s\(^{-1}\)) | \(\sigma_{\text{ring}}\) (km s\(^{-1}\)) | V (km s\(^{-1}\)) |
|-----------|----------------|-----------------|-----------------|----------------|-----------------|-----------------|----------------|
| 343       | 258            | 36              | 20              | 177            | 45              | 29              | 40 ± 2         |
| 352       | 159            | 40              | 13              | 183            | 47              | 27              | 44 ± 2         |
| 362       | 182            | 42              | 8               | 181            | 44              | 24              | 43 ± 1         |
| 372       | 327            | 44              | 15              | 175            | 46              | 23              | 45 ± 1         |
| 381       | 440            | 43              | 12              | 205            | 47              | 25              | 45 ± 1         |
| 390       | 255            | 40              | 18              | 217            | 53              | 28              | 46 ± 2         |
| 400       | 225            | 39              | 20              | 223            | 49              | 25              | 44 ± 2         |
| 409       | 162            | 41              | 29              | 291            | 52              | 26              | 48 ± 2         |
| 418       | 174            | 47              | 20              | 360            | 57              | 29              | 54 ± 1         |
| 428       | 162            | 50              | 42              | 424            | 60              | 32              | 57 ± 2         |
| 437       | 159            | 52              | 33              | 446            | 58              | 36              | 57 ± 2         |
| 446       | 171            | 46              | 31              | 367            | 55              | 27              | 52 ± 2         |
| 456       | 167            | 52              | 25              | 317            | 45              | 24              | 48 ± 2         |
| 466       | 173            | 55              | 23              | 343            | 48              | 28              | 51 ± 2         |
| 475       | 224            | 55              | 29              | 332            | 52              | 30              | 53 ± 2         |
| 484       | 240            | 59              | 45              | 339            | 54              | 28              | 56 ± 2         |
| 494       | 214            | 60              | 28              | 363            | 59              | 28              | 59 ± 2         |
| 503       | 171            | 64              | 36              | 434            | 60              | 22              | 61 ± 2         |
| 512       | 126            | 77              | 33              | 437            | 58              | 31              | 62 ± 2         |
| 522       | 96             | 70              | 15              | 504            | 59              | 37              | 61 ± 2         |
| 531       | 87             | 63              | 12              | 519            | 63              | 36              | 63 ± 2         |
| 540       | 85             | 73              | 32              | 511            | 62              | 37              | 64 ± 2         |
| 550       | 90             | 81              | 45              | 537            | 64              | 41              | 66 ± 2         |
| 559       | 65             | 71              | 30              | 505            | 65              | 39              | 66 ± 2         |
| 568       | 36             | 77              | 17              | 549            | 68              | 36              | 68 ± 2         |
| 578       | 17             | 85              | 25              | 553            | 64              | 35              | 65 ± 2         |
| 587       | 18             | 81              | 4               | 517            | 63              | 35              | 64 ± 2         |
| 595       | 3              | 79              | 4               | 433            | 55              | 42              | 55 ± 2         |
| 606       |                |                 |                 | 465            | 60              | 38              | 60 ± 2         |
| 616       |                |                 |                 | 496            | 67              | 36              | 67 ± 2         |
| 625       |                |                 |                 | 521            | 76              | 37              | 76 ± 2         |
| 634       |                |                 |                 | 531            | 79              | 35              | 79 ± 2         |
| 645       | 8              | 60              | 78              | 518            | 82              | 36              | 82 ± 4         |
| 653       | 19             | 101             | 75              | 513            | 82              | 41              | 82 ± 4         |
| 663       |                |                 |                 | 478            | 71              | 43              | 71 ± 2         |
| 672       |                |                 |                 | 476            | 70              | 36              | 70 ± 2         |
| 682       |                |                 |                 | 462            | 69              | 42              | 69 ± 2         |
Table 5—Continued

| R arcsec | $N_{app}$ | $V_{app}$ km s$^{-1}$ | $\sigma_{ring}$ km s$^{-1}$ | $N_{rec}$ | $V_{rec}$ km s$^{-1}$ | $\sigma_{ring}$ km s$^{-1}$ | $V$ km s$^{-1}$ |
|----------|-----------|----------------------|-----------------------------|-----------|----------------------|-----------------------------|----------------|
| 691      | 465       | 78                   | 38                          |           | 78                   | 38                          | 78 ± 2         |
| 700      | 465       | 88                   | 38                          |           | 88                   | 38                          | 88 ± 2         |
| 710      | 460       | 87                   | 39                          |           | 87                   | 39                          | 87 ± 2         |
| 719      | 421       | 83                   | 31                          |           | 83                   | 31                          | 83 ± 1         |
| 728      | 348       | 85                   | 29                          |           | 85                   | 29                          | 85 ± 2         |
| 738      | 342       | 94                   | 20                          |           | 94                   | 20                          | 94 ± 1         |
| 747      | 323       | 94                   | 20                          |           | 94                   | 20                          | 94 ± 1         |
| 757      | 282       | 95                   | 24                          |           | 95                   | 24                          | 95 ± 1         |
| 766      | 280       | 93                   | 25                          |           | 93                   | 25                          | 93 ± 2         |
| 776      | 255       | 92                   | 34                          |           | 92                   | 34                          | 92 ± 2         |
| 785      | 268       | 97                   | 33                          |           | 97                   | 33                          | 97 ± 2         |
| 794      | 277       | 97                   | 40                          |           | 97                   | 40                          | 97 ± 2         |
| 803      | 215       | 99                   | 46                          |           | 99                   | 46                          | 99 ± 3         |
| 813      | 163       | 101                  | 42                          |           | 101                  | 42                          | 101 ± 3        |
| 823      | 115       | 110                  | 32                          |           | 110                  | 32                          | 110 ± 3        |
| 869      | 61        | 120                  | 14                          |           | 119                  | 14                          | 119 ± 2        |
| 877      | 24        | 103                  | 12                          |           | 102                  | 12                          | 102 ± 2        |

Note. — derived with $V_{sys} = 53$ km s$^{-1}$, $i = 75^\circ$, PA = 52°
Table 6. Parameters of the mass models.

| Model | Galaxy | Type | $(M/L_B)_\star$ | $r_0$ | $\rho_0$ | $c$ | $\chi^2$ |
|-------|--------|------|----------------|-------|----------|-----|--------|
|       |        |      | ($M/pc^3$)     | (kpc) | ($10^{-3}M_\odot/pc^3$) |     |        |
| ISO   | IC 2574| SABm | 0.34           | 5.4   | 7.0      | 10  | 2.7    |
|       | NGC 3109 | SBm  | 0.04           | 2.4   | 2.5      | 6.6 | 2.8    |
|       | NGC 5585 | SABd | 0.85           | 2.2   | 4.3      | 8.2 | 4.4    |
|       | NGC 3198 | SBc  | 4.8            | 2.5   | 5.7      | 9.2 | 7.1    |
| Burkert | IC 2574 |      | 0.6            | 6.0   | 8.4      | 11  | 2.5    |
|       | NGC 3109 |      | 0.35           | 4.1   | 2.5      | 6.6 | 2.9    |
|       | NGC 5585 |      | 0.086          | 4.0   | 4.0      | 8.0 | 8.2    |
|       | NGC 3198 |      | 5.0            | 5.8   | 7.4      | 10  | 7.7    |
| KKBP  | IC 2574 |      | 0.25           | 9.2   | 5.0      | 8.8 | 2.4    |
|       | NGC 3109 |      | 0.40           | 4.5   | 1.5      | 5.2 | 2.9    |
|       | NGC 5585 |      | 0.86           | 3.9   | 5.6      | 9.2 | 7.4    |
|       | NGC 3198 |      | 6.0            | 9.2   | 1.2      | 4.7 | 9.1    |
| NFW   | IC 2574 |      | 0.0            | 35    | 0.05     | 1.0 | 44     |
|       | NGC 3109 |      | 0.0            | 109   | 0.024    | 0.61| 10     |
|       | NGC 5585 |      | 0.0            | 10.1  | 0.77     | 3.9 | 7.9    |
|       | NGC 3198 |      | 3.0            | 11.2  | 1.3      | 4.9 | 44     |

Note. — Models parameters, $r_0$ and $\rho_0$, are respectively the characteristic radius and characteristic density. The concentration $c$ is calculated following Navarro et al. (1996b) and is only exact in the NFW case. Because of the model dependence, $c$ is only approximate for the other cases.
Table 7. MOND parameters when using the best fitted $a_0$.

| Galaxy  | Distance (Mpc) | $a_0$ ($\times 10^{-13}$ km/s$^2$) | $(\mathcal{M}/L_B)_*$ | $\chi^2$ $\mathcal{M}_\odot$/L$_\odot$ |
|---------|----------------|-----------------------------------|------------------------|-----------------------------------|
| IC 2574 | 3.0            | 2.0                               | 0.02                   | 1.5                               |
| NGC 3109| 1.36           | 2.7                               | 0.12                   | 5.0                               |
| NGC 5585| 6.2            | 2.5                               | 0.34                   | 5.9                               |
| NGC 3198| 9.36           | 0.9                               | 6.7                    | 1.1                               |
