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Visiting non-Newtonian MOND gravity in low-mass galaxies

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Abstract. The consistency of the application of Milgrom's modified dynamics (MOND) is tested in low-mass disc galaxies. If the existing Toomre parameter is a good indicator of axisymmetric instabilities, then catastrophic ring instabilities are predicted to occur in the gas component of dwarf gas-rich galaxies. These dynamical instabilites would promote large gas concentrations and would destroy the smoothness of the disc in a few orbit times. As a rule, the attributed property of MOND to explain that the observed rotation curve is a scaled version of the rotation curve derived from the HI alone, may break down. Decreasing the adopted distance to these galaxies in order to recover gas stability is unsatisfactory. These points are illustrated with the low-mass galaxies IC 2574 and NGC 1560, and with the tidal tail in the interacting galaxies NGC 4485/4490.

Key words: gravitation – galaxies: individual: IC 2574 – galaxies: individual: NGC 1560 – galaxies: irregular – galaxies: kinematics and dynamics – cosmology: dark matter

1. Introduction

The modified dynamics proposed by Milgrom (1983), MOND, remains unaccepted by the scientific community because of the absence of a relativistic theory that reduces to MOND in the weak-field limit. Many efforts have been made to test MOND in different astrophysics scenarios (Hernquist & Quinn 1987; Lake 1989; Gerbal et al. 1992; Lo et al. 1993; Gerhard 1993; van der Kruit 1995). However, these results are controversial or inconclusive (see McGaugh & de Blok 1998b for a review), and there is not any definite observational falsification of MOND despite the obvious interest to find it.

On the contrary, MOND can account for the shape and magnitude of a sample of half hundred rotation curves including nearby dwarf galaxies and low surface brightness galaxies, and is able to explain in a natural way the Tully-Fisher relation and other observational trends (Sanders 1996; McGaugh & de Blok 1998b). These facts are striking when one considers that this sample ranges from galaxies with asymptotic rotational velocities between 50 and 300 $\mathrm{km/s}$ and covers a range of 10^3 magnitudes in luminosity. Only the rotation curve for NGC 2841 is badly fitted and requires a distance twice as large as the Hubble law distance for an acceptable fit. Lake (1989) attempted to test MOND with dwarf galaxies and concluded that the constant of acceleration is not universal and should vary systematically with the maximum rotational velocity in the galaxy. However, Milgrom (1991) refuses to be convinced by this sample because of several uncertainties in inclination corrections and distance estimates.

The question that arises is whether is possible a definite test of MOND from galactic dynamics or one has to resort to larger scales such as clusters of galaxies. Deviations from MOND fitting to the observed rotation curves can be justified appealing to various data uncertainties such as non-circular motions, distance errors, imprecise inclination corrections, bulge-disc decomposition, warps, physical variations of the mass-to-light ratio (M/L) of the stellar population with radii, etc.

In this paper, we study the consistency of the application of Milgrom's theory to dwarf disc galaxies for which the uncertainty in M/L is removed because of the dominant contribution of the gas to the potential. For them, MOND prescription successfully reproduces the remarkable structure in the rotation curves of dwarf disc galaxies that dark-halo models are not able to (Begeman et al. 1991). However, these analyses are restricted to reproducing the shape of the rotation curves regardless of the consistency with the internal dynamics given by the theory of spiral structure or of stability against gravitational perturbations.

In this work it is reported that small gas-rich galaxies in MOND would suffer from catastrophic ring instabilities over almost the whole galactic radius. In particular, we focus on the low-mass galaxy IC 2574 for several reasons, such as its high inclination, the existence of HI velocity dispersion data of high accuracy, and other evidence which suggests the absence of strong spiral density waves. Since this galaxy presents a Toomre parameter in MOND less than unity at most galactocentric radii, it should have evolved violently from the present configuration of gas to another more stable one (Sect. 3.1). Generally speaking, it is possible to increase the value of the Toomre parameter by varying the adopted distance for gas-rich galaxies (Sect. 3.2). At present, however, we have not been able to find any satisfactory solution to the problem of stability even invoking magnetic fields (Sect. 4). Indeed, the high degree of instability predicted by MOND in the tidal tail between NGC 4485/4490 seems also to be in conflict with observations (Sect. 5). Overcoming these open questions is necessary for MOND to continue being a real alternative to the dark matter hypothesis in galaxy discs.

2. On the stability of galaxies in MOND

2.1. The Toomre parameter and dwarf galaxies

It is widely accepted that the Toomre parameter Q in galactic discs must lie in the range $1 < Q < 2$ in order to be dynamically cool enough to develop spiral structure but not too cold to be violently unstable to radial instabilities (e.g. Toomre 1981). This constraint has been used, for example, to put limits on the value of the M/L of stellar discs (e.g. Athanassoula et al. 1987; Quillen & Sarajedini 1998; Fuchs et al. 1998). We can ask what are the implications of this constraint in MOND dynamics.

Milgrom (1989) deduced the Toomre condition for local stability of gaseous discs under modified dynamics, $Q_{\rm g}^{\rm MO} > 1$, where $Q_{\rm g}^{\rm MO}$ is related to that of Newtonian dynamics, $Q_{\rm g}^{\rm NE}$, by

$$Q_{\rm g}^{\rm MO} = \mu^+ (1 + L^+)^{1/2} Q_{\rm g}^{\rm NE} = \mu^+ (1 + L^+)^{1/2} \frac{\kappa\, \sigma_{\rm g}}{\pi G \Sigma}, \quad (1)$$

where Σ is the gas surface density, $\sigma_{\rm g}$ is the one-dimensional velocity dispersion of the gas, κ the epicyclic frequency and L^+ is the logarithmic derivative of μ just above the disc, where μ is the MOND function that connects the acceleration in modified dynamics, $\boldsymbol{g}$, with the Newtonian one, $\boldsymbol{g}_N$:

$$\mu\left(\frac{g}{a_0}\right)\boldsymbol{g} = \boldsymbol{g}_{\rm N}. \quad (2)$$

Here $a_0 \simeq 1.2 \times 10^{-8}$ cm s^{-2} is a constant of the theory. The interpolating function must satisfy that $\mu(x) \to 1$ for $x \gg 1$ and $\mu(x) \to x$ for $x \ll 1$.

In the case where the density of the disc and the velocity dispersion are fixed, then disc galaxies with the smallest values of μ^+ will be the most unstable, i.e. dwarf galaxies. In fact, we may express the critical surface density as

$$\Sigma_{\rm c}(R) = \left(\frac{1}{Q_{\rm c}^{\rm MO}}\right) \mu^+ (1 + L^+)^{1/2} \left(\frac{\kappa \sigma_{\rm g}}{\pi G}\right). \quad (3)$$

Just only for illustrative purposes we will assume here that the stability criterion in MOND is obtained from the Newtonian criterion under the substitution $G \to G/(\mu^+(1+L^+)^{1/2})$. Using the same value for $Q_{\rm c}^{\rm MO}$ than Zasov & Bizyaev (1996), the critical surface density expressed in $\left({\rm M}_\odot/{\rm pc}^2\right)$ is

$$\Sigma_{\rm c}(R) \approx 0.23 \times 10^{-3} \left(\frac{\sigma_{\rm g}}{10\,{\rm km/s}}\right) \left(\frac{V_{\rm c}^3}{R^2}\right) \times \left(1 + 0.77 \times 10^{-7} \left(\frac{V_{\rm c}^4}{R^2}\right)\right)^{-1/2} \sqrt{1 + 3\xi}, \quad (4)$$

where $V_{\rm c}(R)$ is the rotation curve in km/s, R is the galactocentric radius in kpc, $\xi = \left(\frac{d \ln V_{\rm c}}{d \ln R}\right)$, and $L = 1$ in the deep MOND limit. To derive Eq. (4) it has been assumed that $\mu(x) = x(1+x^2)^{-1/2}$ (Milgrom 1988) and that $V_{\rm c}^2/R \gg \pi G \Sigma/\mu^+$. It is apparent from Eq. (4) that, in order to maintain, at least, a similar degree of stability for small galaxies with low circular velocity, the surface density of gas should be smaller for them. However, the observed behaviour is the opposite. Small disc galaxies are usually gas-rich galaxies and they do not present any clear spiral pattern or evidence for the existence of density waves.

The stability of the small galaxies IC 2574 and NGC 1560 is studied in detail in the next sections. We show that the values of the Toomre parameter under MOND are very low for these galaxies, even though a very favourable value for stability, $\sigma_{\rm g} = 10$ km/s, is assumed. These galaxies, however, should not be considered as exceptional cases. There are some other galaxies which may present an extraordinary level of axisymmetric instability under modified dynamics, such as NGC 1560, NGC 3109, NGC 55, DDO 9, F561-1 and F565V2. Published HI observations for these galaxies can be found in Broeils (1992), Jobin & Carignan (1990), Puche et al. (1991), Swaters (1997) and de Blok et al. (1996) for the last two, respectively.

Due to the explicit linear dependence of $Q_{\rm g}^{\rm MO}$ on the velocity dispersion of the gas, $\sigma_{\rm g}$, it is worthwhile reviewing the observational and expected trends of $\sigma_{\rm g}$ for different galaxies. This discussion is given in a separate subsection.

2.2. On the HI velocity dispersion in dwarf galaxies

There are many theoretical and observational support to believe that the HI interstellar medium is turbulent even in the outer part of the discs (e.g. Scalo 1987; Sellwood & Balbus 1999). In that case, the assumption used in Eq. (1) that the interstellar medium is homogeneous and uniform breaks down and, consequently, the scale-dependences of the density and velocity dispersion of the gas should be taken into account. However, since the typical scalelength of the instability is greater than the size of the largest eddies, L_0, (L_0 is expected to be of the order of the semi-thickness of the disc, z_0), we may extend the validity of Eq. (1) to turbulent discs.

More dramatic is the dependence of $Q_{\rm g}^{\rm MO}$ on the velocity dispersion; it is clear that stability is recovered by increasing $\sigma_{\rm g}$. From an observational point of view, spiral galaxies in different environments show a remarkably uniform HI velocity dispersion of $\sim$ 6–8 km/s in the outer disc, and a few km/s higher in the bright optical disc (Sellwood & Balbus 1999, and references therein). Different processes to supply the requisite energy to maintain turbulent motions have been proposed, such as supernova heating, differential rotation, gravitational instabilities or MHD driven turbulence.

One could argue that since small galaxies in modified dynamics are very responsive to self-gravity perturbations, these gravitational instabilities are stirring the gas layer to maintain the level of turbulence of the gas for which the condition $Q_{\rm g}^{\rm MO} > 1$ is fulfilled. It is easy to see from simple scaling arguments that this is not the expected situation for low-mass galaxies.

Let $Q_0(R) = \mu^+ (1 + L^+)^{1/2} \kappa \sigma_0/(\pi G \Sigma)$ with $\sigma_0 = 10$ km/s fixed. For some galaxies, it happens that $Q_0 < 1$ between two radius R_1 and R_2 (for IC 2574 see next section). These galaxies require a $\sigma_{\rm g}$ higher than σ_0 to ensure stability. Suppose, in addition, that these galaxies are self-gravitating discs of almost pure gas, as it is deduced from their mass decompositions in Sanders (1996). If the input energy into turbulence, Φ, is driven by gravitational instabilities, the corresponding typical time scale is expected to scale essentially as the dynamical one, i.e. the reciprocal of the angular velocity, Ω^{-1}, so that $\Phi \propto \Sigma\,\Omega$. Furthermore, the dissipation rate of turbulent energy per surface area is $\sigma_{\rm g}^3\Sigma/z_0$, with z_0 the scale height of the disc. Equating the input and dissipation energy rates

$$\sigma_{\rm g}^3 \propto \Omega\, z_0 \simeq \Omega\mu^+ \frac{\sigma_{\rm g}^2}{\pi G\Sigma}, \tag{5}$$

where we have used $z_0 \simeq \mu^+\sigma_{\rm g}^2/(\pi G\Sigma)$ for a stable self-gravitating and isothermal disc. Thus the expected $\sigma_{\rm g}$ in terms of Q_0 is given by

$$\sigma_{\rm g} \propto \left(\frac{\Omega}{\kappa}\right)\left(1+\left(\frac{R\Omega^2}{2a_0}\right)^2+...\right)Q_0. \tag{6}$$

This simple argument shows that the expected value for $\sigma_{\rm g}$ in turbulent discs with low Q_0 should be even smaller that the standard value σ_0, in contradiction with the requirement $\sigma_{\rm g} > \sigma_0$. In other words, the gravitational instability promotes the formation of large gas concentrations instead of being a source of turbulence.

In the unlikely case that the constant internal HI line-width represents the thermal temperature the above arguments are no longer valid. We therefore prefer to present a study of a gas-rich galaxy with measured HI velocity dispersions, IC 2574, to avoid further speculations.

3. The low-mass galaxy IC 2574

IC 2574 is a low-luminosity galaxy ($M_B = -16.99$) (Hidalgo-Gámez & Olofsson 1998) classified as a SXS9 by de Vaucouleurs et al. (1991) and as 9X by Tully (1988). Although this galaxy is classified as a barred spiral in both catalogues, some authors have considered it as a blue compact/irregular dwarf (Masegosa et al. 1991; Miller & Hodge 1994). The spiral arms, if any, are small with almost no star-formation regions. From the HI synthesis observations (Martimbeau et al. 1994), the rotation curve rises slowly, reaching a maximum rotational velocity of $67\,{\rm km/s}$. The inclination is comfortably high ($i = 75^o \pm 7^o$). Non-circular motions are the main source of uncertainties in the inner part.

The neutral interstellar medium of IC 2574 has been extensively studied by Walter & Brinks (1998) from observations with the NRAO Very Large Array with a spatial resolution of 70 pc. Although the HI velocity map is dominated by expanding holes and shells, Walter & Brinks (1998) have been able to infer a HI line-width of 7 ± 1 km/s by looking at quiescent regions and averaging several lines of sight. This value is very similar to those found for other galaxies (e.g. Puche et al. 1992; Dickey 1996; Olling 1996). Interestingly, the HI holes observed in the disc are circular in shape. This can be interpreted as a consequence of the solid-body rotation curve and the absence of strong spiral density waves (Walter et al. 1998).

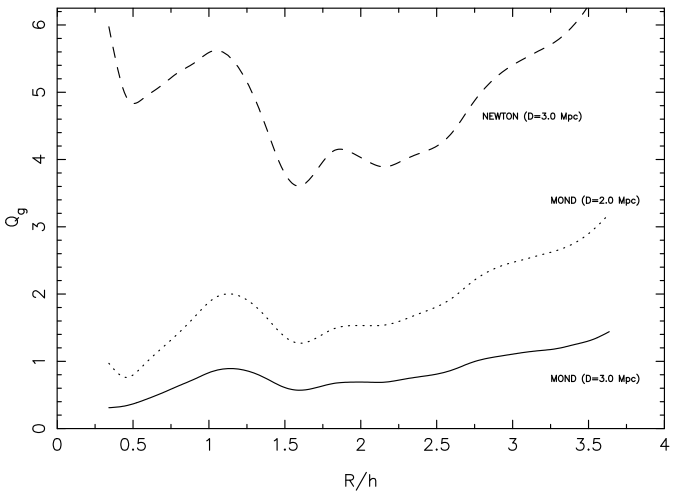

Fig. 1. The Toomre parameter of the gas component of IC 2574 versus galactocentric radius at different adopted distances (h is the scale-length of the disc and $\sigma_{\rm g} = 10\,{\rm km/s}$). For D = 3.0 Mpc in MOND (solid line) and in Newtonian dynamics (dashed line), and for D = 2.0 Mpc in MOND (dotted line).

We are now in a position to calculate the Toomre parameter for the gaseous component of this galaxy under MOND dynamics.

3.1. *Local stability of IC 2574*

Dwarf galaxies have received considerable attention because it is thought that features in the interstellar medium are longer lived than in spirals. In particular, the circular shape of the HI holes in IC 2574 would lead one to think that IC 2574 is presumably rather stable against large-scale gravitational perturbations.

In Fig. 1 $Q_{\rm g}^{\rm NE}$ and $Q_{\rm g}^{\rm MO}$ are plotted in the infinitesimally thin disc approximation, valid because of the relation $z_0 \propto \left(\mu\sigma_{\rm g}^2/\Sigma\right)$ with $\mu \ll 1$ (Milgrom 1983). A distance to this galaxy of $3.0\,{\rm Mpc}$ has been adopted for a direct comparison with previous works. In the MOND case $Q_{\rm g} < 1$ for the most galactocentric radii even with the high adopted $\sigma_{\rm g}$ of $10\,{\rm km/s}$. From this figure it can be concluded that for the adopted distance, the interstellar medium would be very unstable and form rings which would produce catastrophic consequences for the survival of the HI disc.

The most unstable wavelength appears at

$$\lambda_{\rm peak} \simeq \frac{1}{2}\lambda_{\rm crit} \simeq \frac{2\pi^2 G\Sigma}{\mu\,(1+L)^{1/2}\kappa^2} \approx 4\,{\rm kpc}. \tag{7}$$

Thus, the unstable scale is so large that the dispersion relation should be modified to include curvature terms. Nevertheless, it is worthwhile keeping in mind that the WKB results for axisymmetric waves are reasonable for discs under Newtonian dynamics providing $\lambda_{\rm peak}/R \leq 2$.

The corresponding growth time is

$$T_{\rm growth} \;\simeq\; \left(\frac{1+L}{1-Q_{\rm g}^2}\right)^{1/2}\frac{\mu\sigma_g}{\pi G\Sigma}$$

$$= \frac{1}{4\pi}\frac{Q_{\rm g}}{\left(1-Q_{\rm g}^2\right)^{1/2}}T_{\rm orb} \simeq 0.1\,T_{\rm orb}, \tag{8}$$

where $T_{\rm orb} = 2\pi R/V_{\rm c}$ is the orbit time and, for simplification, the superscript MO in $Q_{\rm g}$ has been suppressed. This time-scale for the development of instabilities is significantly shorter than the orbit time, so that the unstable region will respond stronger and faster to this instability than to any potential swing amplification sometimes called global instability. In a few orbit times a large open spiral or a large-scale asymmetry is expected to appear along the galaxy. The early stages of the instability described by the WKB approximation are not different from the case of a massive disc under Newtonian dynamics with the same value of $Q_{\rm g}$ (Milgrom 1989). The observational consequences of such a gravitational instability was discussed by Elmegreen (1996). The further evolution of the disc to these modes is a complicated task because it is non-linear and should be investigated with numerical simulations and the inclusion of star formation. In any case, the predicted distortions in the HI-disc discussed above are in contradiction with the general appearance of the HI distribution in IC 2574. Presumably, the circular shape of the holes reflects the level of stability of the disc. At the very least, this fact confirms the hypothesis that holes, shells and rims have their origin at small-scales and they have no any physical connection with the type of instability we are dealing with.

An important remark must be done at this stage. In calculating $Q_{\rm g}^{\rm MO}$ we used for μ^+ the value at the equatorial plane, say $\mu_{z=0}$, which is strictly valid provided that $V_{\rm c}^2/R \gg \pi G\Sigma/\mu_{z=0}$. The latter requisite is also needed in order to obtain the gravitational acceleration using only the radial component of Eq. (2). As far as we know, all MOND fits to rotation curves available in the literature have been carried out disregarding this point. In the case of IC 2574, the radial and vertical accelerations are comparable in magnitude and, therefore, both the fit to the rotation curve and the Toomre parameter should be recalculated. Nevertheless, it is straightforward to check that the Toomre parameter remains approximately the same. In fact, the ratio between the value of μ^+ after solving Eq. (2) including the vertical acceleration ($\mu^+_{\rm exact}$) and the value used here is approximately the same that the ratio between the respective surface densities. In the deep MOND limit, this ratio is

$$\frac{\mu^+_{\rm exact}}{\mu_{z=0}} \approx \frac{\Sigma_{\rm exact}}{\Sigma_{z=0}} \approx \left(1+\frac{g^2_{{\rm exact},z}}{g^2_{{\rm exact},R}}\right)^{1/2}, \tag{9}$$

where $\boldsymbol{g}_{\rm exact} = (g_{{\rm exact},R},\ g_{{\rm exact},z})$ are the radial and vertical accelerations, respectively.

3.2. Decreasing the distance to IC 2574

Different authors suggest different distance estimates to this galaxy. If IC 2574 is closer than the adopted distance ($D = 3.0$ Mpc), the contribution of the gas to the potential decreases. In this way, it is possible to increase simultaneously the Toomre parameter of the gaseous disc and the stellar mass-to-light ratio until the axisymmetric stability is achieved. From the independent measurements published in the last 15 years, 8 of them were retained here giving an average value of 3.3 ± 0.8 Mpc. Except for the estimate suggested by Bottinelli et al. (1988), the values range between 2.7 and 4.1 Mpc. Moreover, there is strong evidence to believe that IC 2574 belongs to the M81 group which is at a distance of 3.63 ± 0.84 Mpc.

In Fig. 1 the Toomre parameter is also plotted for the case of a significantly lower distance of, say $D = 2.0$ Mpc. Then the gaseous disc becomes self-gravitating with $Q_{\rm g}^{\rm MO} \sim 1.4\,(\sigma_{\rm g}/(10\,{\rm km/s}))$. This is a conservative value if one considers that the observed $\sigma_{\rm g}$ is lower than $10\,{\rm km/s}$ (for the inferred value of 7 km/s, IC 2574 would be marginally unstable even at $D = 2.0$ Mpc) and that the circular shape of the HI holes is an indication of the degree of large-scale gravitational stability. The assumption $D < 2.0$ Mpc alleviates partially the stability problem of the gaseous disc but other concerns arise. In fact, it must be noticed that the needed distance is well outside the acceptable range. But additionally, since the density of the stellar mass must be increased to fit the observed rotation curve, the local stability of the combined gas plus star $Q_{\rm eff}^{\rm MO}$ is suspect. An effective Q-parameter, $Q_{\rm eff}^{\rm NE}$, was suggested by Elmegreen (1995) when both stars and gas contribute.

For low-luminosity galaxies the $Q_{\rm eff}$ parameter is problematic because of its dependence on the stellar velocity dispersion which has not been directly measured because of their low surface brightness. Nevertheless, the young stars borning in the disc from the gas must have the same velocity dispersion than the gas. The stellar velocity dispersion increases with time by dynamical heating mainly caused by scattering of the stars with spiral waves and with giant molecular clouds. Thereby, the stellar velocity dispersion of dynamically low-evolved discs, such as that of IC 2574, may not be appreciably different from the velocity dispersion of the gas component. Besides these arguments, it appears that, from a sample of 12 disc galaxies, the magnitude of the stellar velocity dispersion is proportional to the square root of the surface density, and that larger and more massive discs have larger velocity dispersions (Bottema 1993). An extrapolation of the observational data gives a typical stellar velocity dispersion at one scalelength of $12 \pm 5\,{\rm km/s}$ for this galaxy. If such extrapolation is confirmed, $Q_{\rm eff}^{\rm MO} < 1$ for any distance D. More precisely, $Q_{\rm eff}^{\rm MO}$ would be typically 0.6 at intermediate galactocentric radii even for $D = 2.0$ Mpc. Molecular gas which is expected to be present in self-gravitating discs also contributes to increase the level of instability because of its low velocity dispersion. Generally speaking, the stability of IC 2574 under MOND dynamics is doubful at any D.

In Fig. 2 the best MOND fit for $D = 2.0$ Mpc is plotted but the fit is not as good as for $D = 3.0$ Mpc (see Sanders 1996). The need for decreasing the distance to gas-rich galaxies could have dramatic consequences to the attributed capacity of MOND to reproduce the fine structure of the rotation curves which was a good point in its favour (Begeman et al. 1991; Broeils 1992).

Errors in the adopted inclination, non-circular motions and the beam-smearing effect are the main sources of uncertainties in the HI rotation curve. Because of the high inclination of IC 2574, uncertainties on the inclination do not affect appreciably the inferred rotation curve. Of course, the abundant dust in gas-

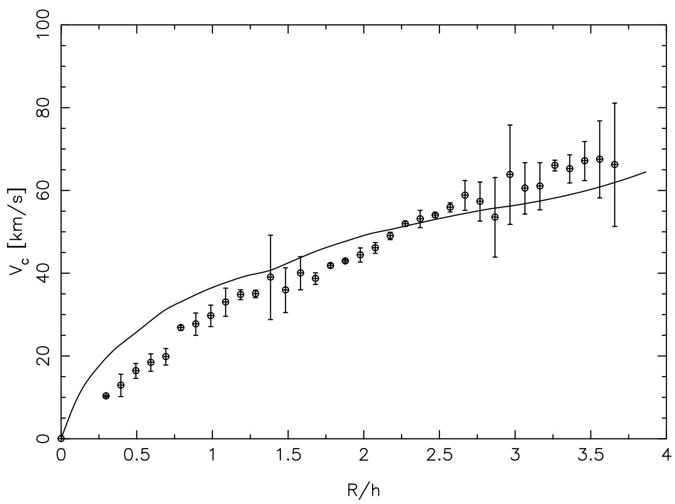

Fig. 2. The observed rotation curve for IC 2574 together with the best fit for an adapted distance of D = 2.0 Mpc ($M/L = 1.1$).

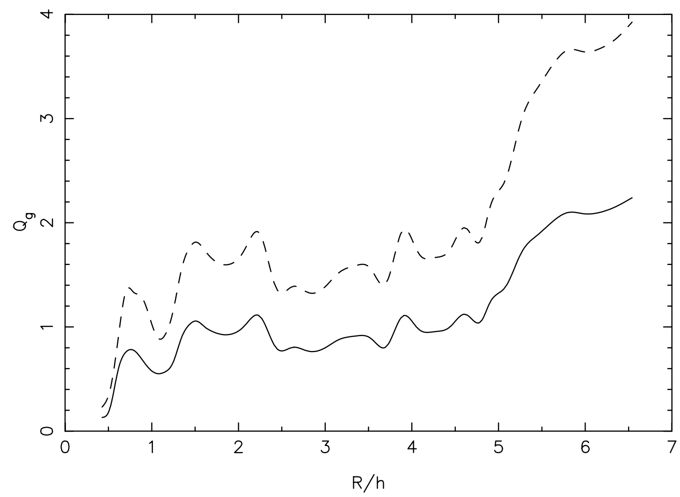

Fig. 3. The Toomre parameter for the gaseous disc of NGC 1560 at D = 3.0 Mpc (solid line) and at D = 2.25 Mpc (dashed line). A value of $\sigma_{\rm g} = 10$ km/s was assumed.

rich galaxies could hide the intrinsic axis ratio of the disc (de Grijs & van der Kruit 1996). Although this is an important point in general, reducing consequently the inclination to $i = 55^o$ (Tully 1988) alleviates only partly the problem of stability. For $i \geq 55^o$ the difference in $Q_{\rm g}$ is very small compared to the accuracy with which $\sigma_{\rm g}$ is estimated. This argument is also valid for other sources of uncertainties in the rotation curve.

Notice also that it is not possible to increase consistently $Q_{\rm g}^{\rm MO}$ by assuming a lower value of a_0.

3.3. Magnetic support

It turns out that errors in the adopted distance cannot be invoked to reach more reasonable levels of stability. Given this situation it is important to find other routes for stability.

Large-scale azimuthal magnetic fields, B_ϕ, may contribute partly to stabilize radial perturbations. In the presence of such a magnetic fields, the Toomre parameter is

$$Q_{\rm M}^{\rm MO} = \mu^+ \left(1 + L^+\right)^{1/2} \frac{(\sigma_{\rm g}^2 + v_A^2)^{1/2}\kappa}{\pi G \Sigma}, \qquad (10)$$

where v_A is the Alfvén velocity. So that, we have

$$\frac{Q_{\rm M}^{\rm MO}}{Q_{\rm g}^{\rm MO}} = \left(1 + 1.4\,\mu^+ \left(\frac{\Sigma}{3\,{\rm M}_\odot/{\rm pc}^2}\right)^{-2} \left(\frac{B_\phi}{1\,\mu{\rm G}}\right)^2\right)^{1/2}. \qquad (11)$$

For the particular case of IC 2574 at $D = 3.0$ Mpc, with $\Sigma \approx 3$ M$_\odot$/pc^2 and for a relatively intense magnetic field of $\sim 2\,\mu$G, the Toomre parameter becomes 1.3 times higher. However, since IC 2574 is nearly pure gas in MOND, the one-fluid Q-parameter is a monotonic indicator for non-axisymmetric instabilities (Binney & Tremaine 1987) even though it was derived for axisymmetric instabilities. This means that although a strong azimuthal field can contribute to stabilize radial perturbations, it is not able to inhibit azimuthal instabilities.

4. NGC 1560 as another selected case

In order to test the capacity of MOND to reproduce the detailed shape of the rotation curves is presented here the fit for the rotation curve of the galaxy NGC 1560 at the maximum distance to ensure at least stability in the gaseous disc. This galaxy is very interesting because it presents a remarkable structure in its rotation curve.

NGC 1560 is a dwarf spiral galaxy which satisfied the criteria of selection proposed by Begeman et al. (1991) to ascertain that the rotation curve is a good tracer of the radial force. The gas is smoothly distributed and reasonably symmetric with respect to the center, and $i = 82^o \pm 1^o$ (Broeils 1992). The MOND fit reproduces successfully the observed curve structure for the adopted distance of 3.0 Mpc (the distance estimates for this galaxy range from 2.9 to 3.7 Mpc). The Toomre parameter of the gaseous disc was calculated with $\sigma_{\rm g} = 10$ km/s and is plotted in Fig. 3 together with that for $D = 2.25$ Mpc. The features in $Q_{\rm g}^{\rm MO}$ come from the mentioned structure in its rotation curve. The predicted MOND rotation curve is drawn in Fig. 4 for the latter distance and $M/L = 2.5$. It is seen that the MOND rotation curve does not reproduce the detailed rotation curve if one requires the existence of a stable disc. For higher M/L the predicted curve becomes completely smoothed. Roughly, the same discussion on the concerns of decreasing the distance given in Sect. 3.2 holds for NGC 1560.

5. The tidal tail in the interacting galaxies NGC 4485/4490

The most severe discrepancy between $Q_{\rm g}^{\rm MO}$ and $Q_{\rm g}^{\rm NE}$ occurs for systems with small accelerations. So that an extremely low $Q_{\rm g}^{\rm MO}$ is expected for gas-rich tidal tails around small galaxies.

A tidal tail of this type has been reported in the closely interacting galaxies NGC 4485 and NGC 4490 which are separated a distance of 7.7 kpc at an assumed distance of 7.8 Mpc. It turns

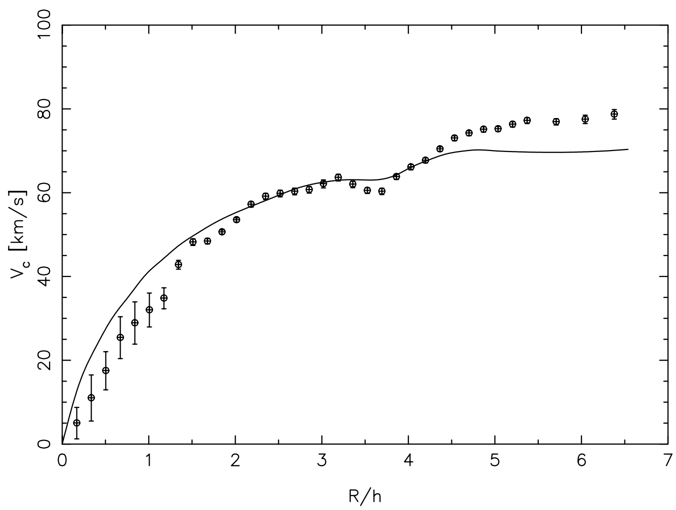

Fig. 4. The predicted MOND rotation curve of NGC 1560 at D = 2.25 Mpc and $M/L = 2.5$.

out an interesting case to compare the predictions of MOND with observations.

Following the observations reported by Elmegreen et al. (1998), the tail has an area of approximately $100'' \times 120''$ ($\sim 1.7 \times 10^7$ pc^2), and a total mass of 1.4×10^8 M$_\odot$. Correspondingly, the mass column density of the tail is 1.8×10^{-3} g cm^{-2}.

The epicyclic frequency, κ, suffers from large uncertainties in the vicinity of the tail due to a possible warp in the disc, which lead to an uncertain rotation curve. From the observed rotation curve of NGC 4490 (Fig. 6 of Elmegreen et al.), $\kappa \sim 10$ km s^{-1}kpc^{-1} and $\mu^+ \simeq (2\pi G\Sigma/a_0)^{1/2} \simeq 0.25$ at the galactocentric radius of 7.5 kpc. But these values could be somewhat different ($\kappa = 15.8$ km s^{-1}kpc^{-1}, $\mu^+ = 0.3$) if we extrapolate the rotation curve as a flat curve. Assuming that the velocity dispersion of the gas in the tail is 10 km/s as observed in the disc of NGC 4490, the range of values for κ and μ^+ yield:

$$Q_{\rm g}^{\rm MO} \simeq 0.3 - 0.6. \quad (12)$$

This high level of instability predicted by MOND seems to be in disagreement with the observations which show that the ages of the youngest regions in the tail are similar to the time since perigalacticon compression by the companion approach, approximately 4×10^8 yr, suggesting a remarkable stability of the tail.

6. Conclusions

Recently, McGaugh & de Blok (1998a,b) have tested thoroughly the hypothesis of dark matter and of modified dynamics. They find that some facts as the Tully-Fisher relation in LSB galaxies are difficult to explain in the dark matter scenario without some fine-tuning between different variables, and are naturally predictable under the modified dynamics hypothesis. Moreover, MOND successfully overcame all the tests done by McGaugh & de Blok. In this sense, this work contributes to assess the viability of MOND. Our main conclusion is that MOND presents severe problems with regard to the question of the local and global stability of small gas-rich galaxies. The local stability of the gaseous component could only be achieved if the adopted distance for these galaxies is smaller than the usual determinations. However, this is not a satisfactory solution because not only the required distance is outside the admissible range, but then MOND fails to explain the property that the observed rotation curve is a scaled version of the rotation curve derived from the HI alone, and the combined gas + star stability of the disc would remain doubful even in this case. A study of the $Q_{\rm eff}$ parameter in modified dynamics may strengthen even more our conclusions.

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