The dynamics of face-on galaxies in MOND

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Abstract. We present an overview of the dynamical analysis using the DiskMass Survey's measurements of vertical velocity dispersions of nearly face-on galaxy disks in both MOND and the standard model of cosmology. We found that the only, even partly realistic, solution is to have galaxy disks that are twice as thin as current surveys suggest. In the standard theory, with cold dark matter, after improving upon the original analysis we found the typical mass-to-light ratios to be less than 0.1 for almost half the sample. This is unrealistically low compared to the 0.6 found by stellar evolution models. Both these issues would disappear if the stellar vertical velocity dispersions were incorrectly measured and are actually 30% larger.

1. Introduction

One of the key goals of the DiskMass Survey ([1, 2, 3] was to unambiguously measure the stellar mass-to-light ratios of disk galaxies. The basic strategy was to simultaneously measure the rotation curve as well as the vertical velocity dispersions of old stars. These old stars should be representative of the mass in the galaxy. They claimed the rotation curve would in principle isolate the dark matter density profile and the vertical velocity dispersions would determine the stellar mass-to-light ratio as a function of radius. A sub-sample of 30 galaxies was described in detail by [4, 5] and led to the conclusion that galaxy disks have stellar mass-to-light ratios that are on average $M_\star/L_K \approx 0.3 M_\odot/L_\odot$ instead of the widely assumed value of $M_\star/L_K \approx 0.6 M_\odot/L_\odot$ which is consistent with maximum disks [6] and the detailed vertical dynamics of the Milky Way [7].

Therefore, in the standard cosmological model, the two data sets for each galaxy give us the dark matter halo profile and the mass-to-light ratio. However, there exist alternative theories of gravity that attempt to explain the dynamics of galaxies without cold dark matter. They have varying degrees of success on different scales, but one that has fared well - particularly on galaxy scales - is Modified Newtonian Dynamics (or MOND[8]).

2. MOND

The salient feature of MOND is that gravity only deviates from the Newtonian prediction below an acceleration threshold in the ultra-weak gravity regime. This deviation occurs for Newtonian predicted accelerations of less than $a_0 = 10^{-10} ms^{-2}$. For accelerations larger than this threshold, the Newtonian acceleration for a spherical potential with mass distribution $M(r)$ is $g(r) = g_N(r) = GM(r)r^{-2}$. Far below the threshold, this becomes

$$g(r) = \sqrt{g_N(r)a_0} > g_N(r). \tag{1}$$

This simple relationship comes from a modified version of Poisson's equation which respects conservation laws. For the full details, one should read [9].

In MOND, since there is no cold dark matter, the rotation curve of each galaxy must be explained purely by the baryonic matter distribution. One can see from Eq 1 that since the gravitational field of all galaxies drops below a_0 in the outer parts, MOND gives flat rotation curves by definition. Not only does MOND give flat rotation curves for reasonable values of the mass-to-light ratio, but it also matches the rotation curve at all intermediate radii for the majority of spiral galaxies.

However, once the rotation curve is fitted - by adjusting the mass-to-light ratio - the full three dimensional gravitational field is specified and no further *broadly* unconstrained parameters exist. This is of course contrary to the cold dark matter scenario where there are two separate mass distributions (the stellar disk and the cold dark matter halo) which have different shapes and extents i.e. the halo is roughly spherical and typically more extended than the disk.

3. Method
In the initial DiskMass Survey analysis (in the cold dark matter framework), they followed the inadvisable route of using the measured vertical velocity dispersions to establish the total surface density. To do this, they employed a highly simplified relation, suggested by [10] at a time when measured vertical velocity dispersions had very large uncertainties. The uncertainties on the DiskMass Survey vertical velocity dispersions are roughly 10% and thus it makes sense to use a more rigorous approach (as suggested in [11]). Using both data sets simultaneously, an iterative process would lead to the ideal stellar mass-to-light ratio and cold dark matter profile. Surprisingly, [5] did not account for the cold dark matter when deriving the stellar surface density from the total surface density, with disastrous results [11]. This is a questionable decision even when stellar disks are maximal, but when stellar disks are extremely light, the cold dark matter becomes highly relevant.

It is much more secure to do the fitting in the reverse manner, i.e., find the gravitational potential from the mass distribution which defines the model rotation curve and use the Jeans equation to determine the model vertical velocity dispersions [9]. The simplest way to find the 3D gravitational potential is to use a Poisson solver, which all N-body codes have. For MOND, a handful of N-body codes exist [12, 13], but we used the most versatile which is [14].

In MOND, this method is obliged by the fact that the vertical gravitational field of a multi-component system is not analytically solvable. To make use of the Poisson solver, one first needs an N-body distribution that is representative of the galaxy being studied. This is achieved by making a bulge-disk decomposition of the radially averaged stellar surface brightness profile, which isolates the bulge and the stellar disk. In addition to this, neutral hydrogen observations give us the surface density of the atomic gas disk and the molecular gas disk is similarly derived. All 3 disk components are observed to be non-smooth, and the N-body distributions reflect this.

3.1. Basic result
In the top left panel of Fig 1, the rotation curve is plotted for one of the galaxies, UGC 4107. In the top right panel, the vertical velocity dispersion profile is plotted for the same galaxy. The mass-to-light ratio - $M_\star/L_K = 0.6$ - required to give a good fit to the rotation curve is given by the black line, which clearly significantly over-predicts the vertical velocity dispersion profile. The mass-to-light ratio - $M_\star/L_K = 0.15$ - required to give a good fit to the vertical velocity dispersion profile is given by the red line, which clearly significantly under-predicts the rotation curve. This is the case for the overwhelming majority of the 30 galaxies in the sample and therefore without another degree of freedom MOND cannot fit the two datasets simultaneously.

In principle, MOND has a number of free parameters that can alter the gravitational field - often significantly. In order to reach agreement with the DiskMass Survey data, it would

help to have an effect that leaves the radial gravitational field unaltered (to fit the rotation curve) and yet reduces the gravitational field in the vertical direction (to fit the vertical velocity dispersions). Varying either the stellar mass-to-light ratio, the MOND acceleration threshold a_0, or the MOND interpolating function ν does not achieve this.

Another option, is to vary the inclination of the galaxy. This can decrease the rotation curve and increase the vertical velocity dispersions, which is the desired effect. However, the scale of the inclination changes are very large (greater than 30%) and this is disfavoured by estimates of the inclinations from scaling relations like the luminous Tully-Fisher relation. The most straight-forward way to fit the measured vertical velocity dispersions with regular mass-to-light ratios is to decrease the thickness of the stellar disk. Although the vertical (and radial) gravitational field would barely be altered, the thinner disk implies the disk must be cold.

It transpires that reducing the disk scale-heights by a factor of two on average enables a good match to the vertical velocity dispersions and rotation curve. As to how this is constrained by other datasets, the stellar scale-heights of nearly face-on galaxies cannot be directly measured because of the projection. However, there is a constraint on the disk scale-heights from observations of edge-on galaxies. For edge-on galaxies, the thickness - determined by the scale-height - across the galaxy can be estimated, assuming the disk has no warp. Simultaneously, the radial scale-length can be deduced. From measurements of the scale-length and scale-height of a sample of edge-on galaxies, [15] demonstrated a clear correlation, which the DiskMass Survey deduced (using additional data) to be $h_z \approx 0.2 h_R^{0.633}$. The simpler relation $h_z = h_R/8$ is also a good match to the data. On average, the unmeasurable scale-heights of the nearly face-on galaxies, with known scale-lengths, should agree with those of the edge-on galaxies.

In all analyses using cold dark matter, performed by us or the DiskMass Survey team, the scale-height was directly inferred using one of the above relations, given the scale-length. In our MOND analysis we used the stellar scale-height as a free parameter to ensure good fits to the measured stellar vertical velocity dispersions, given the mass-to-light ratio required to fit the rotation curve. In the bottom left panel of Fig 1 we plot with green circles the observed scaling relation between scale-height and scale-length measured from observations of edge-on galaxies. The superposed probability density of all data points in the h_z vs h_R plane, which is calculated using the error bars in both dimensions, is shown with the red contours. The fitted scale-heights to achieve good fits in MOND, along with the measured scale-lengths for each DiskMass Survey galaxy are plotted with black triangles accompanied by blue contours. There is clearly a large discrepancy between the two sets of points and their contours. Using a 2D Kolmogorov-Smirnov test we established that the probability for both sets of points originating from the same distribution is less than 10^{-5} regardless of MOND interpolating function.

Therefore, to be consistent with the DiskMass Survey data in MOND, the mass-to-light ratios cannot be varied, and thus are consistent with stellar population synthesis models, but galaxy disks would have to be two times thinner than measured from samples of edge-on galaxies.

On the other hand, in [11] we rigorously analysed the DiskMass Survey data in the cold dark matter theory, correcting for the approximations of [4]. It seems the cold dark model requires K-band stellar mass-to-light ratios lower than 0.1 for roughly half of all galaxies (see Fig 1, bottom right panel), which is basically impossible.

Thus, it appears highly unlikely that the cold dark matter model or MOND are consistent with the DiskMass Survey measurements.

3.2. How reliable is the data?
The key dataset is clearly the stellar vertical velocity dispersions. For this, the DiskMass Survey team use their SparsePak hexagonal grid of 331 science spectral fibers. They have two spectral windows in which the observe each galaxy. In these spectral windows there are certain spectral lines that are very prominent for old giant stars, which should be representative of the old stars

and the I-band or K-band light. The first spectral window is from 500 to 525 nm around the Mg 1b triplet. The second window is around the Ca II triplet at around 860 nm. For each radius bin, there are several fibers located around the annulus, which are shifted in velocity according to the measured rotation curve. The measured spectra in that radius bin are then co-added. To these co-added spectra they separately fit 17 different broadened spectral templates of giant stars ranging from F-giants to K-giants. The required broadening defines the stellar velocity dispersion. In Fig 11 of [2] they show the stellar velocity dispersion for two galaxies: UGC 11356 (top) and UGC 6918 (bottom). For each galaxy, the stellar velocity dispersion is given for the two spectral windows: circles for the Mg 1b triplet and triangles for the Ca II triplet 850nm). The other three panels per row just show various statistics of best fit for each template spectrum when comparing with the observed spectrum. It turns out that the Mg 1b spectrum is well fit by K or G giants with a spread of [165-173] km/s and [57-62] km/s for the top and bottom galaxy respectively. The Ca II spectrum is better fit by M giants because they have stronger lines in that part of the spectrum. This yields 160 km/s for the 1st galaxy (pretty much regardless of template) and 59 km/s for the second. If a wrong template is used, then this second galaxy might give a value as low as 50km/s. So the maximum difference for the first galaxy is 8% and the second is nothing if you choose the "correct" spectrum, but perhaps with a chance of a 20% error. Assuming you just use templates later than K (i.e. K - M ignoring the last template which is always garbage) then the maximum difference is 16%.

Some further questions arise from this. One is whether UGC 11356 and UGC 6918 are representative of the larger sample. UGC 11356 is an elliptical galaxy, not part of the subsample of 30 galaxies and thus hardly relatable. Its velocity dispersion is much higher than the typical average velocity dispersions of the sample. UGC 6918 is probably the least useful of the 30 galaxies. It's worth noting that choosing the "wrong" template ordinarily leads to a lower velocity dispersion, which would make the situation even worse for MOND and cold dark matter.

As to whether the DMS team correctly broadened their spectra to include the velocity dispersion and always chose the correct template for each galaxy and whether this recovered velocity dispersion is consistent with the intrinsic velocity dispersion of the giant stars, we have to rely on the fact that their simulations can be trusted. The details of these simulations, and the original data should be published as soon as possible to allow the community to confirm their findings.

4. Conclusions and discussion

In this contribution, we discussed the corollaries of the DiskMass Survey measurements of vertical velocity dispersions of face-on galaxies. We found that MOND, and basically all modified theories of gravity without dark matter, would require stellar disks that are twice as thin as currently measured to be compatible with the data. In the standard model, the mass-to-light ratios of disks would have to be significantly lower than predicted by models of stellar evolution. Given these unlikely results, we suggest the DiskMass Survey data should be thoroughly double-checked for bugs in the pipeline and stellar template fitting.

5. Acknowledgements

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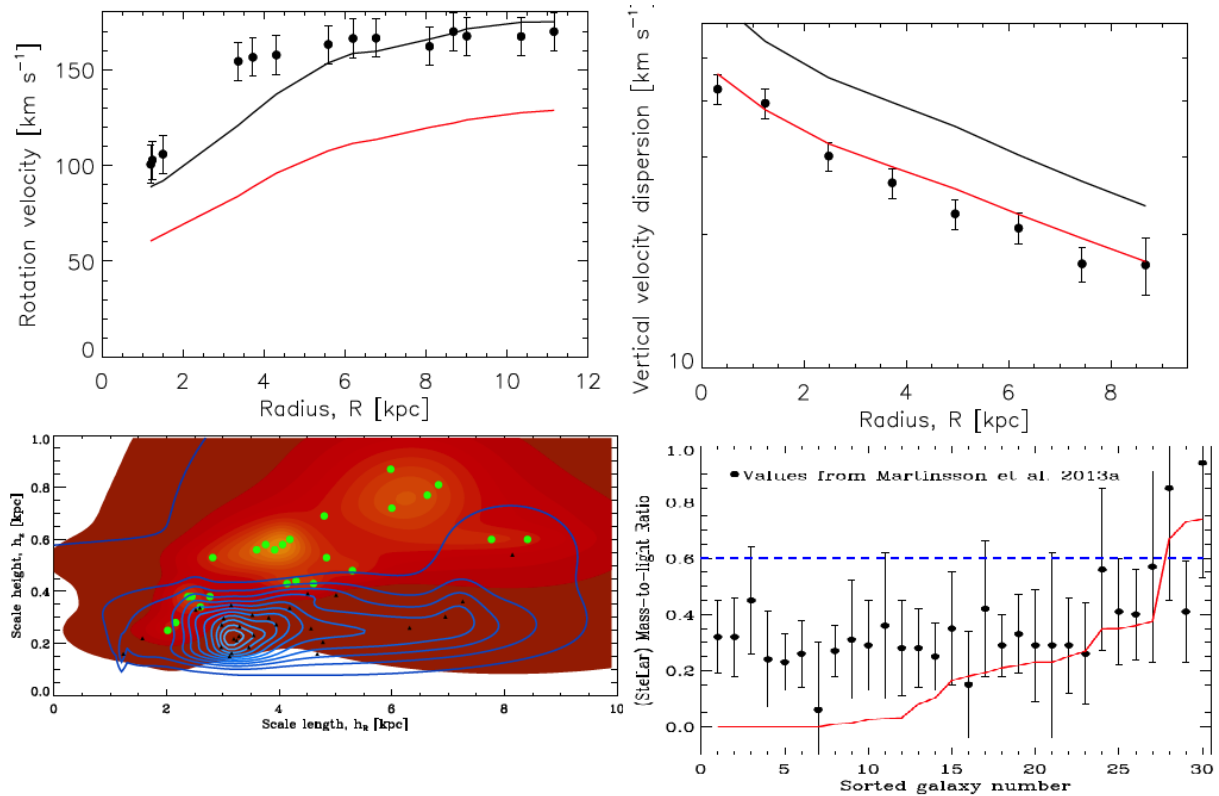
Figure 1. (Top row) Rotation curve (left) and vertical velocity dispersion profile (right) in MOND for UGC 4107 using $M_\star/L_K = 0.6$ (black line) and $M_\star/L_K$=0.15 (red line). (Bottom left panel) Measured scale-lengths and scale-heights for edge-on galaxies (green circles and red contours) and measured scale-lengths with fitted scale-heights to each of the 30 DiskMass Survey galaxies in MOND (black triangles and blue contours). (Bottom right panel) Stellar mass-to-light ratios for each of the 30 DiskMass Survey galaxies in the standard model as measured by (Martinsson 2013b; black cirlces) and by Angus, Gentile & Famaey (2015; red line).

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