Testing MOG theory in the Milky Way

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Introduction

A *dark* component of matter has become one of the pillars of current ΛCDM model: it is invoked to explain the mismatch between the observed dynamical mass, and that inferred by observations of the visible component, of astrophysical objects over a large range of mass and spatial scales, and provides a consistent explanation to the power spectrum of the Cosmic Microwave Background and to the formation of astrophysical structures. Yet, the very nature of this *dark matter* is currently unknown, and none of the proposed candidates has been unambiguously detected yet. An alternative proposal to explain the mismatch observed in the data relies on a modification of the theory of gravity. In this regard, Milgrom proposed the Modified Newtonian Dynamics (MOND) in 1983 which is phenomenologically derived from observations of galaxy rotation curves and the Tully-Fisher relation. A relativistic version of this theory named MOdified Gravity (MOG) [1] was formulated by J. Moffat in 2006. The MOG theory has been able to give an explanation to phenomena around data coming from diverse sources such as motion of globular and galaxy clusters and rotation curves of spiral and dwarf galaxies while there is still a controversy around the posibility that MOG can explain other fenomena such as the Bullet and the Train Wreck merging clusters, among others. So it is currently unclear if MOG phenomenology can offer a solution at all scales. In this work, we only focus on the prediction of MOG theory on the scale of Spiral Galaxies, with a specific one: our own host.

Modified Gravity Theory (MOG)

The MOG theory is a covariant modification of General Gravity that includes a massive vector field ϕ^μ and two scalar fields, G which represents the gravitational coupling strength and μ which corresponds to the mass of the vector field. In order to study the behavior of MOG on astrophysical scales we can use the weak field approximation for the dynamics of the fields. Following [2] the MOG acceleration of a test particle can be obtained from the gradient of the potential, $\vec{a} = -\vec{\nabla}\Phi_{\rm eff}$, yielding the result:

$$\vec{a}(\vec{x}) = -G_N \int \frac{\rho(\vec{x}')(\vec{x}-\vec{x}')}{|\vec{x}-\vec{x}'|^3} \times \left[1+\alpha-\alpha e^{-\mu|\vec{x}-\vec{x}'|}(1+\mu|\vec{x}-\vec{x}'|)\right] d^3\vec{x}'. \quad (1)$$

The resulting force is composed by two components: a Newtonian attraction with a gravitational constant $G_N(1+\alpha)$ and another one, which is repulsive and Yukawa style. These ones, behave in such a way that at large distances, the effective gravity is much stronger than the classical one while weakening at small scales (galactic, subgalactic, or others). The parameters α and μ control the strength and the range of the"fifth force" interaction respectively. In addition, the analysis performed in [3] yields an estimation of the values of α and μ as functions of the source mass M:

$$\alpha = \frac{M}{(\sqrt{M}+E)^2}\left(\frac{G_\infty}{G_N}-1\right) \qquad \mu = \frac{D}{\sqrt{M}} \quad (2)$$

where μ is in units of kpc^{-1}. G_∞ represents the effective gravitational constant at infinity and its value ($\simeq 20G_N$) is established so that at the horizon distance, the effective strengh of gravity is about six times G_N. May it be noticed that in the most general case, α and μ are scalar fields.

Methodology and setup

We test the most common MOG scenarios with data of the rotation curve of the Milky Way. With respect to previous studies of MW data [5], we improve the analysis on two aspects:

- we adopt –separately– two compilations tracers of the rotation curve, that have a higher density of data in the galactocentric distances $2.5 < R < 100$:
  - the compilation of halo star data from [6] (hereafter "Huang et al."), which extends up to 100 kpc,
  - the compilation of tracers `galkin` [7], that offers an enhanced number of diverse types of objects in innermost regions of the MW;
- we implement a full set of three-dimensional observationally-inferred baryonic morphologies including bulge, disk, and gas component, and solve the integral numerically –using the cuba library [9]– in order to obtain the MOG acceleration at each galactocentric distance . We adopt a large array of bulge, and separately disk, density profiles. By combining individually, one bulge, one disc, and the gas component we obtain an array of individual morphologies which bracket the systematic uncertainty on the distribution of the baryonic content within our Galaxy. We follow the technique presented in [8].

The rotation curve for the baryonic component under the MOG potential is compared to the observed rotation curve, building a χ^2 for the angular velocities, adopting the uncertainties on the observed rotation curve and that for baryonic models; for both compilations the data are taken individually, without binning.

Results

We test the MOG theory for each single morphology in our catalogue in its "standard" formulation, adopting the following couple of parameters (α,μ):

- $(\alpha,\mu)^{\rm SG}$ =(8.89, 4.2×10^{-2}), indicated by Moffat as the best possible values to fit the Spiral Galaxies [2],
- $(\alpha,\mu)^{\rm MW}$ =(15.01, $4.3.13\times10^{-2}$), obtained by Moffat as a function of the MW baryonic mass on the basis of Eq. 2 considering $\mathrm{M}^{\rm MW}_{\rm Mof}$=$4\times10^{10}\,\mathrm{M}_\odot$ **[5],**
- $(\alpha,\mu)^{\rm C}$, obteined as the previous one but considering the baryonic mass $\mathrm{M}^{\rm MW}_{\rm C}$ that we self-consistently obtain from our morphological models.

In the following table we present the χ^2 results for some of the morphologies (the full set consists of 30 morphologies). We include the results for the three couple of parameters SG, MW and C, the $\mathrm{M}^{\rm MW}_{\rm C}$ from wich we derive the $(\alpha,\mu)^{\rm C}$ and we also show the newtonian case for comparision. All the analysis is done for both compilations.

baryonic morphology [disk] [bulge]	Newton $\tilde\chi^2$ Huang – galkin	MW $\tilde\chi^2$ Huang – galkin	SG $\tilde\chi^2$ Huang – galkin	C $\tilde\chi^2$ Huang – galkin	$(\alpha,\mu)^{\rm C}$	$\mathrm{M}^{\rm MW}_{\rm C}$ [$10^{10}\,\mathrm{M}_\odot$]
1 [11][12] *G2*	31.83 – 20.15	4.50 – 7.48	4.68 – 7.48	8.59 – 9.81	$(15.79, 2.43\times10^{-2})$	$6.6^{+0.6}_{-0.4}$
2 [17][12] *E2*	32.65 – 21.84	5.02 – 8.54	5.20 – 8.55	9.14 – 10.61	$(15.80, 2.41\times10^{-2})$	$6.7^{+0.7}_{-0.6}$
3 [18][13]	30.14 – 17.82	4.02 – 6.45	4.14 – 6.45	7.71 – 7.98	$(15.84, 2.38\times10^{-2})$	$6.9^{+0.7}_{-0.6}$
4 [18][16]	38.18 – 30.78	7.5 – 13.78	7.87 – 13.78	15.49 – 17.32	$(15.74, 2.47\times10^{-2})$	$6.4^{+0.6}_{-0.5}$
5 [19][15]	36.51 – 23.94	5.68 – 9.93	5.63 – 9.92	9.11 – 10.54	$(15.89, 2.34\times10^{-2})$	$7.2^{+0.7}_{-0.6}$
6 [19][16]	29.76 – 28.70	6.91 – 12.67	6.83 – 12.66	12.91 – 13.88	$(15.85, 2.37\times10^{-2})$	7.0 ± 0.6
7 [20][14]	22.9 – 8.63	1.58 – 1.98	1.32 – 2.00	3.82 – 2.82	$(15.98, 2.26\times10^{-2})$	$7.7^{+0.8}_{-0.7}$

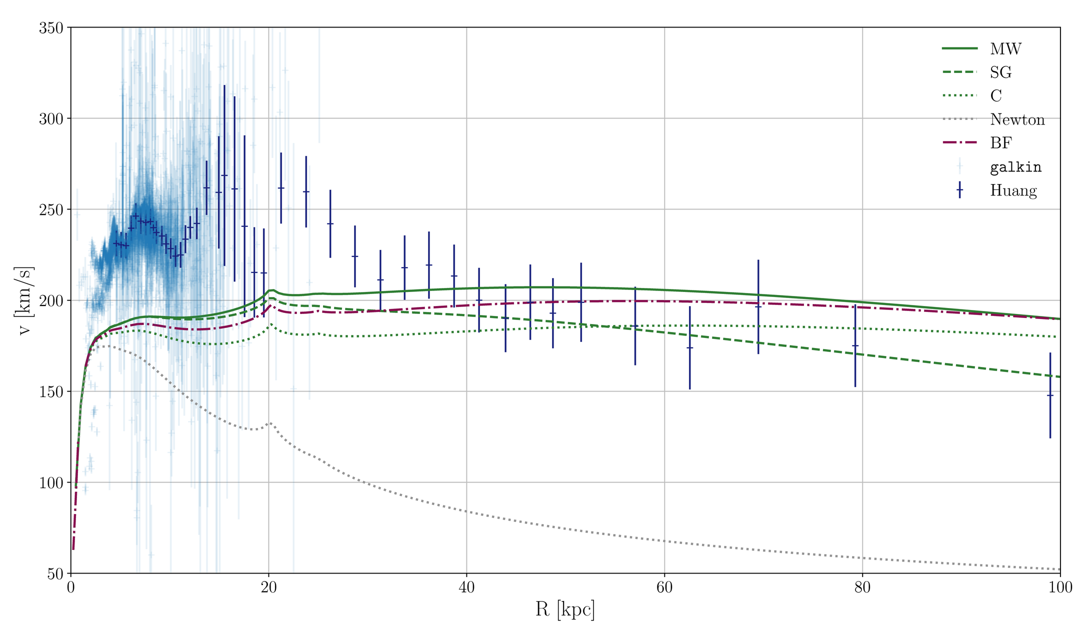
The 5 σ equivalent is $\tilde\chi^2_{5\sigma} = 2.41$ for Huang et al. and $\tilde\chi^2_{5\sigma} = 1.14$) for `galkin`.

Representative morphology

We choose the #2 in the table as our "*representative*" morphology. The reduced χ^2 for the three set of parameters falls beyond the 5 σ equivalent, thus indicating that for this morphology, MOG theory with these parameters is ruled out with a large degree of confidence.

Existing work, [10], assigns an uncertainty to $D = (6.44\pm0.20)\,\mathrm{M}_\odot^{1/2}\mathrm{pc}^{-1}$ and $E = (28.4\pm7.9)\times10^{-3}\,\mathrm{M}_\odot^{1/2}$, which propagates to the values of (α,μ). We obtain the parameter interval $\alpha \in [14.44, 16.43]$ and $\mu \in [2.29, 2.68]\times10^{-2}\,\mathrm{kpc}^{-1}$. We scan this interval, and find that for each point in this two-dimensional space, the reduced χ^2 is beyond the 5 σ equivalent, with the lowest one being $\tilde\chi^2_{BF} = 2.78$ (for Huang et al.), for the parameter point $(\alpha,\mu)_{\rm BF} = (16.59, 2.52\times10^{-2})$.

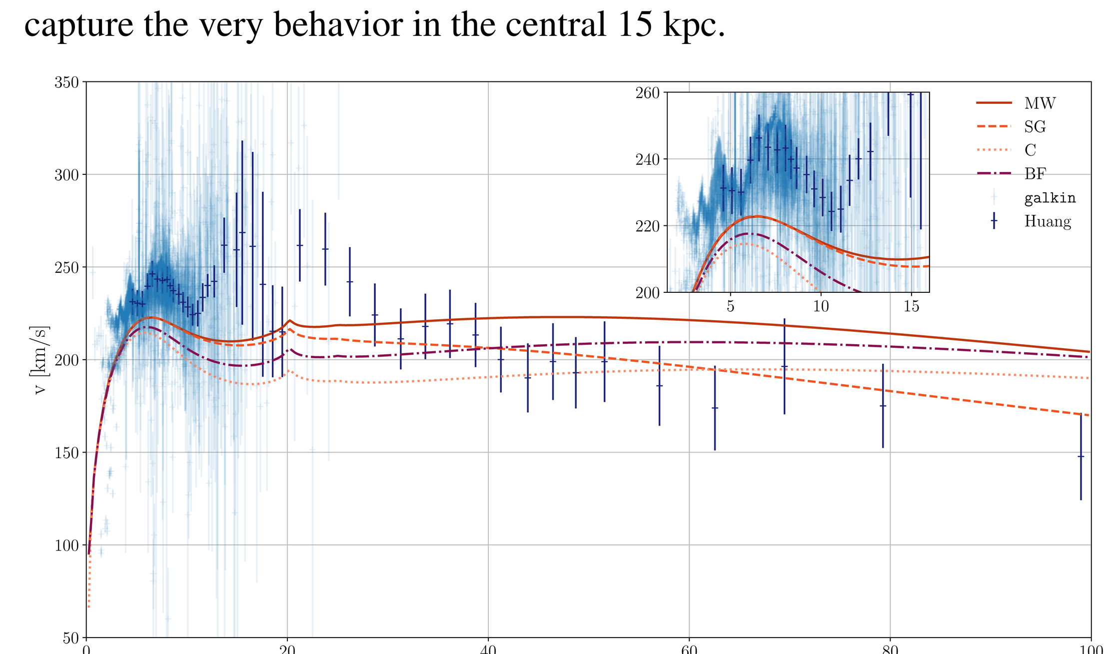
This bears the conclusion that MOG theory fails to explain the observed rotation curve of the Milky Way, for the morphology at study. It may be appreciated from the figure that MOG admittedly performs better than Newtonian gravity, but fails to describe the shape of the observed Rotation Curve.



All morphologies

The same occurs for the entire set of morphologies with the exception of the ones carrying the disk in [20] ("BR disk'). The explanation lies in the fact that the BR disk is the heaviest one among the ones considered, and thus carries the overall normalization of the obtained rotation curve closer to the observed one in the innermost regions.

We select the morphology that produces the best χ^2 (#7 in the table), and we scan the parameter space as done for the representative morphology. The parameter space scanned is $\alpha \in [14.67, 16.59]$ and $\mu \in [2.13, 2.52]\times10^{-2}\,\mathrm{kpc}^{-1}$. Within this range, the best fitting point is $(\alpha,\mu)^{\rm BF} = (16.59, 2.52\times19^{-2}\,\mathrm{kpc}^{-1})$, bearing the reduced $\tilde\chi^2$=2.78 for Huang et al. and $\tilde\chi^2$=2.22 for `galkin`, which is beyond the 5 σ equivalent. While performing better than the representative morphology, as can be seen in the following figure, none of these rotation curves manages to capture the very behavior in the central 15 kpc.



Conclusion

We conclude that the modification of the gravitational potential according to the current version of MOG theory, does not offer a viable solution to the discrepancy between the observed rotation curve, and that generated by the baryons only, in the Milky Way.

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