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Dynamics of disk and elliptical galaxies in Refracted Gravity

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1. INTRODUCTION

We investigate the dynamics of disk and elliptical galaxies with Refracted Gravity (RG) [1,2], a novel classical theory of modified gravity inspired to electrodynamics in matter, which does not resort to dark matter. The presence of dark matter is instead mimicked by a gravitational permittivity, $\epsilon(\rho)$, a monotonic increasing function of the local mass density, ρ, which depends on three universal parameters.

RG was formulated by Matsakos and Diaferio in 2016 [1] and its field equations yield the Poisson equation

$$\nabla \cdot [\epsilon(\rho)\nabla\phi] = 4\pi G\rho \tag{1}$$

modified with respect to the Newtonian one by the presence, at first member, of the gravitational permittivity $\epsilon(\rho)$. In the above equation, ϕ is the RG gravitational potential. The permittivity $\epsilon(\rho)$ has the following asymptotic limits in the high and low density regimes:

$$\epsilon(\rho) = \begin{cases} 1, & \rho \gg \rho_c \\ \epsilon_0, & \rho \ll \rho_c \end{cases}, \tag{2}$$

where $0 < \epsilon_0 \leq 1$ and ρ_c are the gravitational permittivity in vacuum and the critical density, respectively, two of the three free parameters of RG.

Following Eqs. (1) and (2), Eq. (1) reduces to the Newtonian Poisson equation:

$$\nabla^2\phi = 4\pi G\rho \tag{3}$$

in regions where $\rho \gg \rho_c$. Instead, in regions where $\rho \ll \rho_c$, the RG gravitational field is boosted with respect to Newtonian case for a $\epsilon_0 < 1$.

RG predicts a different behavior of the gravitational field for spherical and not spherical systems. For spherical systems, the gravitational field, obtained by integrating Eq. (1), is equal to:

$$\frac{\partial\phi}{\partial r} = \frac{G}{\epsilon(\rho)}\frac{M(<r)}{r^2} \tag{4}$$

where $M(<r)$ is the mass of the system enclosed within the spherical radius r. In this case, we do not observe a redirection of the field lines: the RG field has the same direction and r-dependence as the Newtonian case, proportional to r^{-2} in the outermost regions of galaxies, and it is enhanced by $\epsilon(\rho)^{-1}$. The focusing of the field lines is instead observed in non-spherical configurations. Expanding the first member of Eq. (1), we obtain:

$$\frac{\partial\epsilon}{\partial\rho}\nabla\rho \cdot \nabla\phi + \epsilon(\rho)\nabla^2\phi = 4\pi G\rho \tag{5}$$

where the term "$\frac{\partial\epsilon}{\partial\rho}\nabla\rho \cdot \nabla\phi$" is different from 0 in non-spherical systems and causes the refraction of the field lines toward the mid-plane of the object. The analogy with the electrodynamics in matter is, thus, observed in non-spherical systems. This refraction process implies, for the radial component of the gravitational field, $\frac{\partial\phi}{\partial R}$, the asymptotic limit $\frac{\partial\phi}{\partial R} \sim \left(a_0 \left|\frac{\partial\phi_N}{\partial R}\right|\right)^{1/2} \propto R^{-1}$ in regions of $\rho \ll \rho_c$ at large distances R from the center of galaxies, where $\frac{\partial\phi_N}{\partial R}$ is the radial component of the Newtonian gravitational field and $a_0 =$

1.2×10^{-10} m s^{-2} is the MOND [3] critical acceleration. MOdified Newtonian Dynamics (MOND) [3] is a theory of modified gravity where Newtonian gravity breaks down in low-acceleration environments, where $a \ll a_0$, and shows numerous successes on galaxy scale [3,4]. Being this asymptotic limit identical to the MOND one, in low-acceleration regions, the successes of MOND on galaxy scale are likely to be shared by RG.

In our work, we want to test whether RG can reproduce the dynamics of galaxies independently of their shape, either flat or spherical, or, in other words, whether the boost of the RG gravitational field is determined by the gravitational permittivity alone, independently of the focusing of the force lines. To perform this study, we model with RG the kinematic profiles of 30 disk galaxies belonging to the DiskMass Survey (DMS) [5] and of three elliptical E0 galaxies, NGC 1407, NGC 4486, namely M87, and NGC 5846, from the SLUGGS survey [6]. We choose these galaxy samples for the following reasons:

1. being DMS galaxies close to face-on, both their rotation curves and their vertical velocity dispersion profiles are available and, modeling two kinematic profiles at the same time rather than the rotation curves alone provides a more stringent constrain for RG;
2. having ellipticities between 0.85 and 1 [6], E0 galaxies can be approximated as spherical systems and they are ideal to test whether RG can model the dynamics of galaxies with this morphology. The kinematics of the galaxies in the SLUGGS survey is probed up to $\sim$10 effective radii from their centers thanks to the detection of two populations of globular clusters (GCs), a blue and a red one. Constraining the properties of RG from such extended kinematic profiles of two distinct populations provides again a very stringent test for RG.

To perform our analysis, we adopt this smooth step function for the gravitational permittivity:

$$\epsilon(\rho) = \epsilon_0 + (1 - \epsilon_0)\frac{1}{2}\left\{\tanh\left[\ln\left(\frac{\rho}{\rho_c}\right)^Q\right] + 1\right\} \quad (6)$$

where Q is the third free parameter of the theory and regulates the steepness of the transition between the Newtonian and the RG regimes. Specifically, the larger the value of Q the steeper the transition (see Fig.1 of [2]). Summarizing, RG has three free parameters, ϵ_0, Q and ρ_c, supposed to be universal.

2. EXPERIMENTS AND RESULTS

2.1. Disk galaxies

2.1.1. Mass model

The results of this work are collected in [2]. We model the rotation curves and the vertical velocity dispersions perpendicular to the galaxy disks from the mass distributions of 30 disk galaxies in the DMS. We describe their mass density profiles with a stellar disk, a spherical stellar bulge and an atomic and a molecular gas components. To model the mass density of the stellar disk, $\rho_d(R, z)$, we adopt a linear interpolation of its measured surface brightness, $I_d(R)$, to properly reproduce the observed features of the rotation curve, following the Renzo's rule [7]. We multiply this profile by a declining exponential profile along the z-direction perpendicular to the disk plane, obtaining:

$$\rho_d(R, z) = \frac{\Upsilon}{2h_z} I_d(R) \exp\left(-\frac{|z|}{h_z}\right) \quad (7)$$

where h_z is the disk-scale height and Υ is the disk mass-to-light ratio, two of the free parameters of the kinematic model.

We model the surface brightness of the stellar bulge with a spherical Sérsic profile,

$$I_{\rm b}(R) = I_{\rm e} \exp\left\{-7.67\left[\left(\frac{R}{R_{\rm e}}\right)^{\frac{1}{n}} - 1\right]\right\} \tag{8}$$

convolved with a gaussian point spread function to take the seeing into account. In Eq. (8), $R_{\rm e}$ is the effective radius, which encloses half of the bulge luminosity, $I_{\rm e}$ is the bulge surface brightness at $R = R_{\rm e}$ and n is the Sérsic index. To obtain the bulge mass density, we deproject Eq. (8) with the Abel integral:

$$\rho_{\rm b}(r) = -\frac{\Upsilon}{\pi}\int_r^{+\infty} \frac{{\rm d}I_{\rm b}(R)}{{\rm d}R}\frac{{\rm d}R}{\sqrt{R^2 - r^2}} \tag{9}$$

where we adopt the same mass-to-light ratio Υ as the stellar disk.

We model the atomic and molecular gas components as razor-thin disks, where the linear interpolation of the measured surface mass density, $\Sigma_{\rm atom,mol}(R)$, is multiplied by a Dirac delta function in the z-direction, $\delta(z)$:

$$\rho_{\rm atom,mol}(R,z) = \Sigma_{\rm atom,mol}(R)\delta(z). \tag{10}$$

The total density profile is given by the sum of the four components:

$$\rho(R,z) = \rho_{\rm d}(R,z) + \rho_{\rm b}(r) + \rho_{\rm atom}(R,z) + \rho_{\rm mol}(R,z) \tag{11}$$

For greater details on the mass model of DMS galaxies, see Appendix A of [2]. To derive the RG gravitational potential, ϕ, from the mass density $\rho(R,z)$ (Eq. (11)) of each galaxy, we numerically solve the RG Poisson equation (1) with a successive over relaxation Poisson solver, detailed in Appendix B of [2].

2.1.2. Rotation curves

To test RG, we first model the rotation curves of DMS galaxies on their own. The model of the rotation curve is obtained by equaling the centripetal and the gravitational forces on the mid-plane of the disk, $z = 0$:

$$v(R,z=0) = \sqrt{R\frac{\partial\phi(R,z)}{\partial R}}. \tag{12}$$

The model has five free parameters: the mass-to-light ratio, Υ, the disk-scale height, h_z, and the three free parameters of RG, ϵ_0, Q, and $\rho_{\rm c}$. To explore the parameter space, we employ a Monte Carlo Markov Chain (MCMC) algorithm with a Metropolis-Hastings acceptance criterion. For convenience, we explore the space of $\log_{10}\rho_{\rm c}$, rather than of $\rho_{\rm c}$. Further details on the MCMC algorithm and on the priors adopted for the free parameters of the model, are presented in [2]. As estimators and uncertainties on the free parameters of the model we adopt the medians of the MCMC chains and the interval between the 15.9 and the 84.1 percentiles that include the 68% of the posterior cumulative distribution centered on the median, respectively. This choice is justified by the fact that the posterior distributions of the parameters show a single peak.

RG models the rotation curve of each DMS galaxy rather well, also capturing some of the features of the measured profile corresponding to the features of the measured surface brightness, thanks to the linear interpolation that we adopt to describe the stellar disk surface brightness. The mass-to-light ratios Υ required to model the rotation curves agree within 3σ with the mass-to-light ratios predicted by the stellar population synthesis (SPS) models of [8], $\Upsilon_{\rm SPS}$, for 24 out of 29 galaxies (the galaxy UGC 3997 is excluded from the comparison since its $\Upsilon_{\rm SPS}$ cannot be computed, given that its $B - K$ color is not reported in [9]). To model the rotation curves, RG also requires disk-scale heights h_z generally consistent with the disk-scale heights $h_{z,\rm SR}$ estimated from the following relation between the disk-scale heights h_z and the disk-scale lengths h_R derived from the observations of edge-on galaxies [10]:

$$\log_{10}\left(\frac{h_R}{h_{z,\mathrm{SR}}}\right) = 0.367\log_{10}\left(\frac{h_R}{\mathrm{kpc}}\right) + 0.708 \pm 0.095. \quad (13)$$

2.1.3. Rotation curves and vertical velocity dispersion profiles

To provide a more stringent test for RG, we include the stellar vertical velocity dispersion profiles in our modeling. In particular, we model, at the same time, the rotation curve and the vertical velocity dispersion profile of each DMS galaxy. The model of the vertical velocity dispersion profile derives from Jeans analysis:

$$\sigma_z^2(R) = \frac{1}{h_z}\int_0^{+\infty}\left[\int_z^{+\infty} \exp\left(-\frac{|z'|}{h_z}\right)\frac{\partial\phi(R,z')}{\partial z'}\mathrm{d}z'\right]\mathrm{d}z. \quad (14)$$

This expression considers only the luminosity contribution of the stellar disk and neglects the contribution of the bulge, being the average bulge-to-total luminosity ratio equal to 0.09 for DMS galaxies. In this study, we adopt the same MCMC algorithm and the same priors and estimators on the free parameters of the model as in the analysis for the rotation curves alone.

RG properly reproduces both kinematic profiles of DMS galaxies with mass-to-light ratios Υ consistent within 3σ with the respective Υ_{SPS} for 26 out of 29 galaxies. Yet, adding the vertical velocity dispersion profiles in our modeling, the resulting disk-scale heights decrease with respect to the analysis with the only rotation curves and they are ~2 times smaller than the $h_{z,\mathrm{SR}}$ derived from the observations of edge-on galaxies with Eq. (13). Also Angus and collaborators [11], that performed the same analysis with QUMOND, a modified gravity version of MOND [12], found a similar result. However, this result is not due to an issue of the two theories of modified gravity but to an observational bias [13,14]. Indeed, the h_z estimated from the vertical velocity dispersions and the $h_{z,\mathrm{SR}}$ are derived from two distinct stellar populations: whereas the spectroscopic signal that provides the vertical velocity dispersions, from which we estimate our h_z, is dominated by a younger stellar population, with a smaller velocity dispersion and disk-scale height, the photometric signal from which Eq. (13), and thus $h_{z,\mathrm{SR}}$, is inferred is dominated by an older stellar population, with a larger velocity dispersion and disk-scale height. By artificially increasing the vertical velocity dispersion profiles of 5 galaxies in the DMS sample by an appropriate factor, consistent with the results of [14], the estimated disk-scale heights are now consistent with the $h_{z,\mathrm{SR}}$.

2.1.4. A unique combination of RG parameters

In our two previous analyses, we estimated the three RG parameters, ϵ_0, Q and $\log_{10}\rho_{\mathrm{c}}$, for each individual DMS galaxy. Yet, the RG parameters should be, in principle, universal. The distributions of the three RG parameters derived from each galaxy have standard deviations either smaller than or comparable to the mean errors on these parameters. This means that the differences between the values found from the individuals galaxies might be due only to statistical fluctuations, suggesting that a single combination of RG parameters is likely to be found to describe the kinematics of the entire sample.

To find this combination, we set the Υ and the h_z to the values estimated from the rotation curves and the vertical velocity dispersion profiles of the single galaxies (Sect. 2.1.3) and we only explore the space of the three RG parameters, modeling the rotation curves and the vertical velocity dispersion profiles of the 30 galaxies at the same time. By considering the entire sample at the same time, the computational effort increases: we, thus, parallelize the C++ code with OpenMP, being each galaxy independent from the others. The program is publicly available on GitHub, at the link https://github.com/alpha-unito/astroMP, and is described in [15].

The universal combination of parameters is equal to $\{\epsilon_0, Q, \log_{10}[\rho_{\mathrm{c}}(\mathrm{g/cm^3})]\} = \{0.661^{+0.007}_{-0.007}, 1.79^{+0.14}_{-0.26}, -24.54^{+0.08}_{-0.07}\}$ and it is consistent, within 2σ, with the average parameters $\{\epsilon_0, Q, \log_{10}[\rho_c(\mathrm{g/cm^3})]\} = \{0.56 \pm 0.16, 0.92 \pm 0.71, -25.30 \pm 1.22\}$ found for the individual galaxies, supporting the assumed universality of these parameters. As expected, by adopting this unique combination of ϵ_0, Q, and $\log_{10}\rho_c$ for the entire sample, the description of the kinematic profiles of the galaxies generally worsen, mainly due to the rotation curves but, for about half sample, both kinematic profiles are well reproduced. Given this result, we expect that, adopting a less approximate approach, we might find a universal combination of RG parameters consistent with the one found with this analysis that properly models the kinematic profiles of all the 30 DMS galaxies.

2.1.5. The radial acceleration relation

Besides the rotation curves and the vertical velocity dispersion profiles, we want to test whether RG can reproduce the radial acceleration relation (RAR) of DMS galaxies. The RAR neatly quantify the mass discrepancy in galaxies and the function

$$g_{\mathrm{obs}}(R) = \frac{g_{\mathrm{bar}}(R)}{1 - \exp\left(-\sqrt{\frac{g_{\mathrm{bar}}(R)}{g_\dagger}}\right)} \quad (15)$$

fits the RAR derived from all the galaxies in SPARC sample [16] with the only one free parameter $g_\dagger = (1.20 \pm 0.02 \pm 0.24) \times 10^{-10}\mathrm{m\ s^{-2}}$, consistent with MOND acceleration scale a_0 [17]. The RAR has a very small observed scatter of 0.13 dex, consistent with the scatter of 0.12 dex due to observational errors, and, if marginalizing over observational errors, the RAR has an even smaller intrinsic scatter of 0.057 dex [17,18]. Moreover, the RAR might show no correlations between the residuals from Eq. (15) and the galaxy properties [19].

We build the RAR of DMS data, with the Υ found in Sect. 2.1.3. and $h_z = h_{z,\mathrm{SR}}$, and we compute the models of the RAR in RG from the parameters determined in Sect. 2.1.3. RG models a RAR with the correct asymptotic limits of Eq. (15) but with an intrinsic scatter of 0.11 dex, larger than expected. Moreover, the RG models of the RAR show strong correlations, at more than 5σ, with some galaxy properties. Yet, also the RAR of DMS data shows some, even if weaker, correlations, between its residuals and some galaxy properties, apparently at odds with the results of [19] for SPARC. Further investigations are required to assess whether this result is due to an issue of RG or it depends on the galaxy sample.

2.2. Elliptical galaxies

2.2.1. Kinematic model

The results of this work are reported in Cesare et al. in preparation. To test whether RG can also reproduce the dynamics of spherical systems, we model the root-mean-square velocity dispersions of stars, blue GCs, and red GCs of NGC 1407, NGC 4486, and NGC 5846, three elliptical E0 galaxies belonging to the SLUGGS survey [6]. For each galaxy, we model the velocity dispersions of the three tracers at the same time. The kinematic profiles of the two GCs population are from ~ 5 (NGC 1407) to ~ 50 (NGC 4486) times more extended than the kinematic profiles of the stars and are, thus, decisive to constrain RG. We derive our model of the root-mean-square velocity dispersion of each tracer $\mathrm{t} = \{S, B, R\}$, where "S" are the stars, "B" the blue GCs and "R" the red GCs, from spherical Jeans analysis:

$$V_{\mathrm{rms,t}}^2(R) = \frac{2}{I_{\mathrm{t}}(R)} \int_R^{+\infty} K\left(\beta_{\mathrm{t}}, \frac{r}{R}\right) \nu_{\mathrm{t}}(r) \frac{\mathrm{d}\phi}{\mathrm{d}r} r\mathrm{d}r. \quad (16)$$

In the above equation, R and r are the projected and the 3D radii, $I_{\mathrm{t}}(R)$ is either the surface brightness of the stars or the surface number density of blue and red GCs, $\nu_{\mathrm{t}}(r)$ is either the 3D luminosity density of the stars or the 3D number density of blue and red GCs, $\frac{d\phi}{dr}$ is the RG gravitational field, given by Eq. (4), β_t is the orbital anisotropy parameter of each tracer t, assumed to be constant with R, and $K\left(\beta_t, \frac{r}{R}\right)$ is a kernel function, given by the first expression in Eq. (A16) of [20]. We model the surface brightness of the stars in NGC 1407 and the surface number density of GCs in all three galaxies with a Sérsic profile, whereas we model the surface brightness of the stars of the other two galaxies with the Multi-Gaussian Expansion approach [21,22].

The total baryonic mass and the total baryonic mass density that enter Eq. (4) and set the galaxy gravitational potential that regulates the dynamics of the three tracers are given by the sum of the contributions of the stars, the hot X-ray emitting gas, and the central supermassive black hole. We neglect the contribution of the GCs, given that their relative mass fraction with respect to the total mass is always smaller than 1%.

This model has seven free parameters: the galaxy mass-to-light ratio Υ and the three RG parameters, setting the galaxy potential well, and the anisotropy parameters $-\log_{10}(1-\beta_t)$ for the three individual tracers. The adopted MCMC algorithm and the estimators for the free parameters are the same as for disk galaxies and the priors on the free parameters are described in Cesare et al., in preparation.

2.2.2. Results

RG generally provides a good description of the kinematic profiles of the three populations in all three galaxies. Only some points of the measured profiles of the blue GCs in NGC 4486 and NGC 5846 are not properly interpolated by the RG curves. This result might be due to a too approximate modeling: indeed, we treat the three galaxies as isolated systems, whereas they settle at the centers of galaxy groups or clusters, whose gravitational influence could affect the models.

The mass-to-light ratios required to model the velocity dispersions of the three galaxies are in agreement with the expectations from SPS models and the anisotropy parameters are consistent with the literature [23]. The RG parameters found from each individual galaxy are in agreement with each other within ~1σ, further suggesting their universality. The Q and $\log_{10}\rho_c$ parameters are also consistent, within 3σ, with the universal parameters found from the entire DMS sample (Sect. 2.1.4). Yet, a 10σ tension occurs between the ϵ_0 found from the three E0 galaxies and from the DMS. Further studies are required to assess whether this issue is due either to a fundamental problem of RG, namely Eq. (1) is wrong, or to a limitation of Eq. (6) for the gravitational permittivity, or to our approximated model, where the galaxies are assumed to be isolated and their interacting environment is not taken into account. Anyway, ϵ_0 becomes consistent within $\sim 2\sigma$ if we refer to the average parameter of the individual DMS galaxies, listed in Sect. 2.1.4, rather than to the value estimated from the entire DMS sample.

2. CONCLUSIONS

In our work, we verify that RG can reproduce the dynamics of both flat and spherical systems. RG can properly model both the rotation curves and the vertical velocity dispersion profiles of 30 disk galaxies in the DMS and the root-mean-square velocity dispersions of stars, blue GCs, and red GCs of three elliptical E0 galaxies in the SLUGGS survey, showing that the boost of the gravitational field only depends on the gravitational permittivity and not on the refraction of the RG force lines.

RG describes the kinematic profiles of both samples of galaxies with sensible mass-to-light ratios, consistent with SPS models. RG models the kinematic profiles of DMS galaxies also with disk-scale heights in agreement with the observations of edge-on galaxies and the kinematic profiles of the elliptical galaxies with anisotropy parameters consistent with the literature.

To account for the rotation curves and the vertical velocity dispersion profiles of the DMS galaxies, RG requires RG parameters from the different individual galaxies consistent with each other, suggesting their universality. As expected from this result, the entire DMS sample can be modeled, as a whole, with a unique combination of RG parameters, in agreement with the parameters from the individual galaxies.

To model the velocity dispersions of the three kinematic tracers in the three E0 galaxies, the theory also needs RG parameters in agreement with each other. These Q and $\log_{10}\rho_c$ parameters are also consistent with the values estimated from the entire DMS sample. Yet, the ϵ_0 parameters derived from the two galaxy samples show a 10σ tension. Future studies are needed to understand whether this problem is due to the theory itself, to a too approximate profile for the gravitational permittivity, or to a too simplified modeling, that treats the E0 galaxies as isolated systems rather than embedded in galaxy groups or clusters.

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