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MOND VS. NEWTONIAN DYNAMICS IN EARLY-TYPE GALAXIES: THE CASE OF NGC 4649 (M60)

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Abstract. The kinematics of the early-type galaxy NGC 4649 (M60) is used in order to compare the predictions of two different approaches regarding the existence of unseen matter in its outer parts: modified Newtonian dynamics (MOND) and the classical Newtonian dynamics. We use the recently published kinematical data of NGC 4649 out to $\sim 6R_{\rm e}$ (where $R_{\rm e}$ is the effective radius) which were obtained using globular clusters (GCs) to calculate the full velocity profile. We then compare thus obtained values of the velocity dispersion with the predictions of the spherical Jeans equation. We show that the Jeans models based on the constant mass-to-light ratio model and different MOND models provide a good agreement with the observed values of the velocity dispersion. The best fits of the velocity dispersion were obtained using the mass-to-light ratio in the B-band equal to 7 implying that there is no need for large amounts of dark matter in the outer parts (beyond $\sim 3R_{\rm e}$) of this galaxy. We also find that tangential anisotropies are present in NGC 4649.

1. INTRODUCTION

The problem of dark matter in early-type galaxies is still one of the most important unsolved problems in the contemporary extragalactic astronomy and cosmology (e.g. Samurović 2007, Chap. 1, for a detailed introduction). For decades it was almost universally assumed that the giant ellipticals are paramount reservoirs of dark matter, a prejudice partially based on the poor understanding of the Faber-Jackson relation linking the central velocity dispersion and the galactic luminosity. The general picture which seems to emerge with contemporary observational data suggests that interior to ∼2–3 effective radii $R_{\rm e}$ (inner regions), dark matter does not play any important dynamical role (e.g. Samurović and Danziger 2005). At larger galactocentric distances (beyond $\sim$ 3-4$R_{\rm e}$) it starts to play more important role; its contribution, however, varies from case to case (e.g. Samurović and Danziger 2006, Samurović 2006; see Samurović and Ćirković 2008b regarding NGC 4649). In general, there is still considerably smaller amount of observational data for elliptical than for spiral galaxies, which makes establishing general results very difficult.

Although the presence of non-baryonic dark matter in the Universe is widely accepted, some alternatives have been expressed such as the theory of MOND (Modified Newtonian dynamics, Milgrom 1983; recent review in Milgrom 2008). The case for giant ellipticals has not been considered adequately and one possible reason is the scarcity of available kinematical data out to large galactocentric distances. Several attempts to model ellipticals with dark matter and/or MOND theory have appeared (e.g. Schuberth et al. 2006, Tiret et al. 2007, Richtler et al. 2008) with ambiguous results. Notably, Tiret et al. (2007) claimed that a MOND model for the dynamics of NGC 3379 reproduced the observations on all scales, while Richtler et al. (2008), studying NGC 1399, reached the opposite conclusion – that the best-fit MOND model still requires an "additional hypothetical dark halo". The latter result is essentially equivalent to rejection of the MOND hypothesis, since its original motivation would be obviated by such a result, if confirmed.

In the present work we analyze the galaxy NGC 4649 using MOND and the classical Newtonian dynamics; the details are given in Samurović and Ćirković (2008a,b).

2. OBSERVATIONAL DATA

NGC 4649 (M60) is a giant elliptical galaxy in the Virgo cluster that has a nearby companion, NGC 4647 (Sc galaxy at 2.′5 from the center of NGC 4649). The systemic velocity of NGC 4649 is $v_{\rm vel} = 1117 \pm 6\ \ {\rm km\,s^{-1}}$. We consider two values for the distance to NGC 4649: (i) the first one, $d = 17.30$ Mpc is based on the surface brightness fluctuation method and is taken from Lee et al. (2008) (in this case, one arcsec corresponds to 84 pc); and (ii) the second one is based on the systemic velocity, which implies that using $h_0 = 0.70$, we obtain $d = 15.96$ Mpc, for which one arcsec corresponds to 77.5 pc. In our models we used both values of the distance in order to find the best fit to the observed data. For the effective radius, we assume the value of $R_{\rm e} = 90$ arcsec (equal to 7.56 kpc for $d = 17.30$ Mpc, and 6.97 kpc for $d = 15.96$ Mpc), which is the value taken from the paper by Kim et al. (2006).

We used the data related to the observations of GCs in NGC 4649 presented by Lee et al. (2008). The sample consists of 121 GCs (83 blue and 38 red GCs). In all of our calculations, we always considered the entire sample. We presented the kinematics of NGC 4649 in Fig. 1 from Samurović and Ćirković (2008a): velocity, velocity dispersion and s_3 and s_4 parameters which describe asymmetric and symmetric departures from the Gaussian, respectively. We found that the velocity dispersion remains approximately constant ($\sigma \approx 230\ \ {\rm km\,s^{-1}}$) throughout the entire galaxy. We also determined the negative value of the s_4 parameter ($s_4 \approx -0.03$) which indicates tangential anisotropies; this is in agreement with the estimates found in the literature (Bridges et al. 2006; Hwang et al. 2008).

3. MODELS

We modelled the observed velocity dispersion beyond 1 arcmin (because our observationally based points are all beyond ~ 1 arcmin) using the Jeans equation (e.g. Binney and Tremaine 1987):

$$\frac{{\rm d}\sigma_r^2}{{\rm d}r} + \sigma_r^2 \frac{(2\beta_* + \alpha)}{r} = -\frac{GM(r)}{r^2} + \frac{v_{\rm rot}^2}{r} \tag{1}$$

where σ_r is the radial stellar velocity dispersion, $\alpha = {\rm d}\ln\rho/{\rm d}\ln r$ is the slope of tracer density ρ (the surface density is given in Samurović and Ćirković (2008a) and in the models below we used $\alpha = -2.285$). The rotation speed $v_{\rm rot}$ was found to be non-zero, i.e. $v_{\rm rot} = 141^{+50}_{-38}\ \ {\rm km\,s^{-1}}$ (Hwang et al. 2008). A parameter β_* is introduced

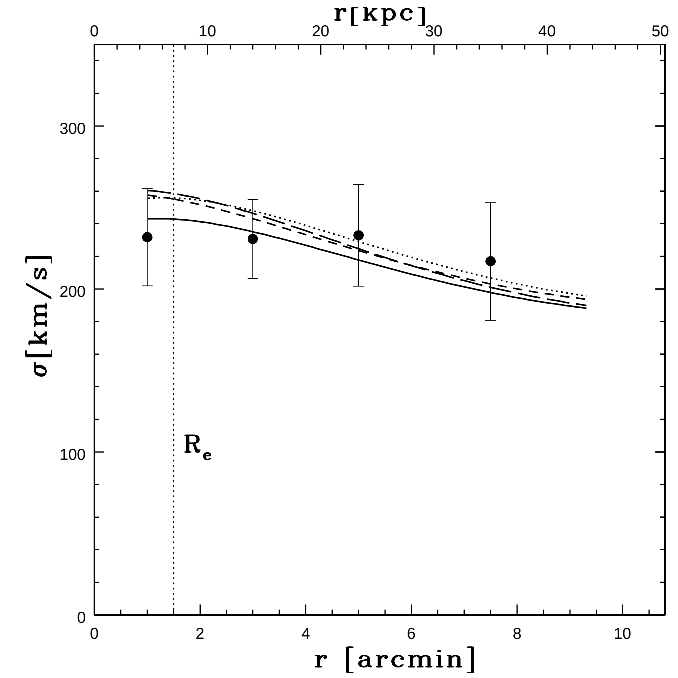

Figure 1: Jeans modeling of NGC 4649 using $M/L_{\rm B} = 7$ for the Newtonian and MOND approach. Solid line is the best fit for the Newtonian constant mass-to-light ratio model and is obtained using $\beta_* = -0.2$. The three MOND models are given as follows: dotted line is for the "standard" model for which $a_0 = 0.93 \times 10^{-8}$ cm s^{-2} and $\beta_* = -0.3$, long-dashed line is for the "simple" model for which $a_0 = 1.35 \times 10^{-8}$ cm s^{-2} and $\beta_* = -0.4$ and short-dashed line is for the "toy" model for which $a_0 = 1.35 \times 10^{-8}$ cm s^{-2} and $\beta_* = -0.5$. The distance $d = 17.30$ Mpc was always used.

to describe the non-spherical nature of the stellar velocity dispersion:

$$\beta_* = 1 - \frac{\overline{v_\theta^2}}{\sigma_r^2}, \tag{2}$$

where $\overline{v_\theta^2} = \overline{v_\theta}^2 + \sigma_\theta^2$. For $0 < \beta_* < 1$, the orbits are predominantly radial, and the line-of-sight velocity distribution is more strongly peaked than a Gaussian profile (positive s_4 parameter), and for $-\infty \leq \beta_* < 0$ the orbits are mostly tangential, so that the profile is more flat–topped than a Gaussian (negative s_4 parameter). In all our models, we calculated the projected line-of-sight velocity dispersion.

4. RESULTS

The results of our modelling are given in Fig. 1 (see also Figs. 3 and 4 from Samurović and Ćirković (2008a)). Here we briefly summarize our major findings.

4. 1. NEWTONIAN MODELS

For constant mass-to-light ratio models, we consider relations that include stellar mass and dark matter distributed in the form of the standard Hernquist (1990) profile:

$$\rho_{\rm H}(r) = \frac{M_{\rm T}}{2\pi}\frac{a}{r}\frac{1}{(r+a)^3}, \tag{4}$$

which has two parameters: the total mass $M_{\rm T}$ and scale length, a, where $R_{\rm e} = 1.8153a$. We solved the Jeans equation (Eq. 1) and considered values of $M/L_{\rm B}$ between 7 and 15, while noting that $M/L_{\rm B}\gtrsim 10$ is incompatible with an entirely stellar component. The following values of the mass-to-light ratio were tested: low ($M/L_{\rm B} = 7$), intermediate ($M/L_{\rm B} = 10$), and high ($M/L_{\rm B} = 15$, includes at least $\sim 50\%$ of dark matter). In all cases, we allowed a realistic variation in both the β_* parameter and the distance to the galaxy, d for the fixed value of the mass-to-light ratio. The best-fitting model has the following parameters: lower mass-to- light ratio, $M/L_{\rm B} = 7$, slightly tangential orbits, $\beta_* = -0.2$, and the distance $d = 17.30$ Mpc. We note that a good fit can also be achieved for a higher value of the mass-to-light ratio but then the β_* parameter increases and the orbits become isotropic. This result implies that dark matter is not playing an important dynamical role, even beyond $\sim 3R_{\rm e}$. The value of the constant mass-to-light ratio $M/L_{\rm B} \sim 7$ means that the total mass of NGC 4649 is equal to $\sim 5\times 10^{11} M_\odot$ at $\sim 3R_{\rm e}$.

4. 2. MOND MODELS

We calculated the total mass of NGC 4649 in MOND gravity using three different formulas: (i) the "simple" MOND formula from Famaey and Binney (2005), (ii) the "standard" formula (Sanders and McGaugh 2002), and (iii) the Bekenstein's "toy" model (Bekenstein 2004). We write the Newtonian acceleration as $a_{\rm N} = a\mu(a/a_0)$, where a is the MOND acceleration, $\mu(x)$ is the MOND interpolating function where $x \equiv a/a_0$, and $a_0 = 1.35^{+0.28}_{-0.42}\times 10^{-8}$ cm s^{-2} is a universal constant. The interpolation function $\mu(a/a_0)$ shows an asymptotic behavior, $\mu \approx 1$, for $a \gg a_0$, and we derive the Newtonian relation in the strong field regime, and $\mu = a/a_0$ for $a \ll a_0$. The MOND dynamical mass, $M_{\rm M}$, can be expressed in terms of the Newtonian values, $M_{\rm N}$ using the following expression (e.g. Angus et al. 2007):

$$M_{\rm M}(r) = M_{\rm N}(r)\times\mu(x). \tag{5}$$

The calculated values of the total mass interior to 4 arcmin for different MOND approaches are the following: $\sim 8\times10^{11} M_\odot$ (for the "standard" model), $\sim 7\times10^{11} M_\odot$ (for the "simple" model) and $\sim 5\times10^{11} M_\odot$ (for the "toy" model). We refer the reader to Samurović and Ćirković (2008b, Table 1 and Fig. 1) for more details regarding comparison of the total mass of NGC 4649 inferred using different approaches.

We solved the Jeans equation (Eq. 1) based on the Hernquist profile (Eq. 4), where $M_{\rm T}$ is calculated using Eq. 5. We varied different parameters: distance d, parameter a_0, and anisotropy β_*. The lower mass-to-light ratio ($M/L_{\rm B} = 7$) provides a good fit to the observed velocity dispersion for all tested models. The preferred value of the constant $a_0 = 1.35\times 10^{-8}$ cm s^{-2} was found in two cases (for the "simple" and "toy" model), whereas a lower value was found for the "standard" model, $a_0 = 0.93\times 10^{-8}$ cm s^{-2}. In all tested models, we found that there is a detection of tangential anisotropy, the largest extent for the "toy" model ($\beta_* = -0.5$) and the smallest extent for the "standard" model ($\beta_* = -0.3$). It is important to emphasize that we cannot exclude higher (but not extremely high) mass-to-light ratio in our models; for example, the "toy" model with $M/L_\mathrm{B} = 9$, $a_0 = 0.93 \times 10^{-8}$ cm s^{-2}, $d = 17.30$ Mpc, and $\beta_* = -0.3$ also provides a satisfactory fit to the observed data.

The same conclusion regarding the dynamical importance of dark matter, reached in the case of the constant mass-to-light ratio, also holds for the Jeans models based on MOND: successful fits were obtained without dark matter throughout the entire galaxy for all MOND approaches.

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