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THE IMPORTANCE OF DARK MATTER IN NEARBY EARLY-TYPE GALAXIES

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Abstract. In this contribution we present the study of the dynamics of the sample of ten early-type galaxies in both Newtonian and MOND approaches. We use the measurements of the radial velocities of globular clusters detected in the galaxies in the sample to test the predictions of dynamical models with and without dark matter out to several effective radii. We solve the Jeans equations for both the Newtonian (mass-follows-light and dark matter models) and MOND approaches (three different MOND models) assuming spherical symmetry; for both approaches we assume various values of velocity anisotropy. We compare thus obtained estimates of the mass-to-light ratios with results obtained using stellar population synthesis models. We find that the Newtonian mass-follows-light models without significant amount of dark matter can provide successful fits for only one galaxy (NGC 2768), and for the remaining nine early-type galaxies various amounts of dark matter are required in the outer parts. With MOND models, we find that four early-type galaxies can be fit without dark matter and that the remaining six galaxies require an additional dark matter component to successfully fit the observed velocity dispersions.

1. INTRODUCTION

The problem of the existence and distribution of dark matter (DM) in early-type (elliptical and lenticular) galaxies remains poorly understood. In Samurović (2007) we listed the main reasons why early-type galaxies are studied to a lesser degree than their spiral counterparts. The studies of these galaxies performed so far show that some galaxies such as NGC 5128 appear to lack DM, or at least DM is not dynamically important out to approximately 6 effective radii (R_{e}) (Samurović 2010). Samurović (2012) recently analyzed the massive elliptical galaxy NGC 4472 and found that beyond $\sim 2R_{\mathrm{e}}$ DM or modifications of Newtonian dynamics are necessary to successfully fit the observed velocity dispersion.

In analogy with spirals, it is expected that all early-type galaxies also contain a significant amount of DM and analyses of early-types usually relied on Newtonian dynamics. However, the MOND (MOdified Newtonian Dynamics) theory, (Milgrom 1983) which was well tested on spirals, has proved to be capable of successfully fitting early-type galaxies as well. Its basic assumption is that the acceleration due to the gravitational force does not depend simply upon the mass m as in the Newtonian approach, but has a more complex form, $m/\mu(a/a_0)$, where a_0 is a universal constant, taken to be $a_0 = 1.35^{+0.28}_{-0.42} \times 10^{-8}$ cm s^{-2} (Famaey et al. 2007).

In the present study, we analyze a sample of ten massive early-type galaxies taken from the SLUGGS (SAGES Legacy Unifying Globulars and Galaxies Survey) database (available at `http://sluggs.swin.edu.au`) (Pota et al. 2013, hereafter P13). We use globular clusters (GCs) as tracers and consider both Newtonian (mass-follows-light or with additional Navarro, Frenk & White (1997, NFW) DM) and MOND dynamics (without DM), assuming isotropic, slightly tangential or increasingly radial orbits. The best-fit mass-to-light ratios are then compared with the results of various stellar population synthesis (SPS) models in order to assess the importance of DM at a given radius of a given galaxy in the sample. More details are available in Samurović (2014, hearafter S14).

In the MOND theory the interpolating function $\mu(x)$ is used assuming several forms: for $a \gg a_0$ the Newtonian acceleration is restored ($\mu = 1$), whereas for $a \ll a_0$ the interpolation function becomes $\mu = a/a_0$.

The galaxies from our sample are objects with a wide range of luminosities, morphological types (within the early-type class) and from different environments (from field galaxies to members of groups and clusters). We used the observational data from P13 and we decided to include in our sample ten out of twelve galaxies: NGC 1400, NGC 1407, NGC 2768, NGC 3115, NGC 3377, NGC 4278, NGC 4365, NGC 4486, NGC 4494 and NGC 5846. P13 split the GCs of each galaxy into blue and red population, we however chose to work with a *total* sample of GCs for each galaxy in order to have more clusters per bin because our goal is to determine as accurately as possible the velocity dispersion and departures from the Gaussian in the distribution of GCs. We assume the dimensionless Hubble constant $h_0 = 0.70$.

2. DYNAMICAL MODELS

For all ten early-type galaxies in our sample we solve the Jeans equation (e.g. Binney & Tremaine 2008) in a spherical approximation for both approaches, Newtonian and MOND:

$$\frac{\mathrm{d}\sigma_r^2}{\mathrm{d}r} + (\alpha + 2\beta)\frac{\sigma_r^2}{r} = a_{\mathrm{N;M}} + \frac{v_{\mathrm{rot}}^2}{r}, \tag{1}$$

where $a_{\mathrm{N;M}}$ is an acceleration term which is different for each approach: in the Newtonian ('N') approach it is equal to $a_{\mathrm{N}} = -GM(r)/r^2$ and for MOND ('M'), a_{M} satisfies (Milgrom 1983):

$$a_{\mathrm{M}}\,\mu\left(\frac{a_{\mathrm{M}}}{a_0}\right) = a_{\mathrm{N}}. \tag{2}$$

In eq. (1), σ_r is the radial stellar velocity dispersion, $\alpha = \mathrm{d}\ln\nu/\mathrm{d}\ln r$ is the slope of tracer density ν. The details and relevant plots are available in S14.

The non-spherical nature of the GC dispersion is expressed through the following well-known equation, $\beta = 1 - \frac{\overline{v_\theta^2}}{\sigma_r^2}$, where $\overline{v_\theta^2} = \overline{v_\theta}^2 + \sigma_\theta^2$ and $0 < \beta < 1$ means that the orbits are predominantly radial, whereas for $-\infty \leq \beta < 0$ the orbits are mostly tangential. We tested three cases of anisotropies: the isotropic case ($\beta = 0$), the mildly tangential case for which there is a hint from the observed kinematics ($\beta = -0.20$) and the theoretically based value ($\beta_{\mathrm{lit}}(r) = \beta_\infty r/(r + r_a)$), where $\beta_\infty \simeq 0.5$ and $r_a \simeq 1.4R_{\mathrm{e}}$; this estimate (radially dominated) comes from theoretical expectations from merging collisionless systems (Mamon & Łokas 2005).

3. RESULTS AND CONCLUSIONS

In Newtonian approach, for a constant mass-to-light ratio model we used a constant mass-to-light ratio (M/L_*) Sérsic model that uses a galaxy's field stars. DM is added to the stellar component in the form of an NFW DM halo.

We tested several MOND models using the Jeans equation in the spherical approximation: (i) the "simple" MOND formula from Famaey & Binney (2005), (ii) the "standard" formula (Sanders & McGaugh 2002), (iii) the Bekenstein's "toy" formula (Bekenstein 2004). The expressions, in terms of the Newtonian circular velocity and the radius, for the circular velocity obtained with MOND using these three formulae are given in Samurović & Ćirković (2008).

The best-fit values for each tested model are compared with the estimates coming from several SPS models (see S14 for details).

We used GCs as a tracer of the potential of the sample of ten early-type galaxies. To infer the existence of DM we used the Newtonian (mass-follows-light and stars + NFW DM) models and MOND models to calculate the mass-to-light ratios, which were compared with the predictions of various SPS models based on the stellar matter.

Our most important results and conclusions (see Table 1) are:

- We found that *only one* galaxy can be modeled with a single value of the constant M/L ratio approximately consistent with the value of the stellar component showing the lack of significant amount of DM: NGC 2768. Three more galaxies (NGC 1400, NGC 3377 and NGC 4494) show the increase of the total mass-to-light ratio with radius, which suggests the existence of DM in them. NGC 4486 is the only galaxy that needs significant amount of DM in its inner region. The remaining five galaxies require significant amount of DM beyond $\sim 2-3R_{\rm e}$ to explain their dynamics inferred using GCs: NGC 1407, NGC 4278, NGC 4365 (this galaxy because of its large effective radius requires significant amount of DM beyond one effective radius) and NGC 3115 require DM beyond $\sim 3R_{\rm e}$, whereas in NGC 5846 DM becomes important beyond $\sim 2R_{\rm e}$ and NGC 4486 requires DM in its inner parts (interior to $\sim 0.35R_{\rm e}$). For the effective radii of NGC 4365 and NGC 4486 we took the values of 184.22 and 703.91 arcsec, respectively (Kormendy et al. 2009). The largest estimated mass-to-light ratio was found in NGC 5846 for which $64.2 < M/L_B < 127.4$ beyond $\sim 6R_{\rm e}$ was established; the lowest mass-to-light ratio was found in NGC 4494 for which we find $2.6 < M/L_B < 5.7$. The NFW models provided the best fits for all the galaxies in the sample.

- We also solved the Jeans equation in the spherical approximation for three different MOND models (standard, simple and toy). We found that the following galaxies could be modeled with mass-to-light ratio consistent with the no dark-matter hypothesis assuming the values of the M/L ratios consistent with the stellar mass only: NGC 1400, NGC 2768, NGC 3377, and NGC 4494. The following galaxies require DM even in the MOND approach in their outer parts: NGC 1407, NGC 4278, NGC 5846 and NGC 3115 require DM beyond $\sim 3R_{\rm e}$ and NGC 4365 and NGC 4486 require DM exterior to $\sim 1R_{\rm e}$ (~ 20.7 kpc) and $\sim 0.35R_{\rm e}$ (~ 15 kpc), respectively.

Table 1: Summary of the results and conclusions

name	N-noDM (int)	N-noDM (out)	N-DM (int/out)	M-noDM (int)	M-noDM (out)
(1)	(2)	(3)	(4)	(5)	(6)
NGC 1400	$\surd$	–	$\surd$	$\surd$	$\surd$
NGC 1407	$\surd$	–	$\surd$	$\surd$	–
NGC 2768	$\sim$	$\sim$	$\surd$	$\surd$	$\surd$
NGC 3115	–	–	$\surd$	$\surd$	–
NGC 3377	$\surd$	–	$\surd$	$\surd$	$\surd$
NGC 4278	–	–	$\surd$	$\surd$	–
NGC 4365	–	–	$\surd$	$\surd$	–
NGC 4486	–	–	$\surd$	–	–
NGC 4494	$\surd$	$\surd$ –	$\surd$	$\surd$	$\surd$
NGC 5846	$\surd$	–	$\surd$	$\surd$	–

NOTES: 'N' is for Newtonian models and 'M' is for MOND models and 'DM' ('noDM') indicates the existence (lack) of dark matter in a given object; "int" is interior region (interior to $\sim 3R_e$) and "out" is exterior region (exterior to $\sim 3R_e$). Two exceptions are the galaxies NGC 4365 and NGC 4486: their inner regions are interior to 1 $R_{\rm e}$ and 0.35 $R_{\rm e}$, respectively. The sign "$\sim$" for galaxy NGC 2768 denotes that this galaxy can be fit with a constant mass-to-light ratio, but the value obtained is marginally higher than that predicted by SPS models. The combination of signs ("$\surd$ –") for NGC 4494 denotes that the mass-to-light ratio obtained for this galaxy in its outer parts is consistent with the value obtained using SPS models, but because of the increase of the mass-to-light ratio in its outer part, one cannot exclude the existence of DM (see S14 for details).

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