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# TWO TYPES OF DARK MATTER DISTRIBUTION IN EARLY-TYPE GALAXIES

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**Abstract.** If one wants to explain the observed dynamics of galaxies, one is faced with the fact that gravitational force needed is greater than that which is produced by the visible matter. This leads to the introduction of the dark matter (DM) hypothesis. In this contribution we describe our sample of 15 early-type galaxies (ETGs) which includes both ellipticals and lenticulars. For all the galaxies in our sample we extract full kinematic profiles out to several effective radii: we rely on globular clusters (GCs) and we calculate the mass-to-light ratios of all the galaxies using the Jeans equation. We parametrize the gravitational field by that produced by the stars and a Navarro-Frenk-White DM halo. We focus on the relation between the dynamically inferred gravitational acceleration and the acceleration expected from the distribution of the visible matter (the acceleration relation, AR). The AR is nearly universal for the spiral galaxies, in agreement with the MOND modified dynamics theory. Up to now, observational difficulties precluded investigating the AR in the ETGs. Here we show that a few of our ETGs also follow very tightly the AR for the spiral galaxies, while the majority shows substantial deviations. That the first group might be spiral galaxies that lost their gas support the facts that they rotate, have disky isophotes, appear mostly very elongated and have blue colors. The galaxies deviating from the AR for the spirals either disprove MOND or contain unobserved matter.

## 1. INTRODUCTION

The missing mass problem is far from being solved. While the usual explanation is the dark matter (DM), the theories suggesting modifications of the standard laws of physics are still viable. Among these theories, MOND (Milgrom 1983) is particularly popular and successful. It roughly states that the actual gravitational acceleration, $a$, is a function of the gravitational acceleration calculated in the Newtonian way from the distribution of the visible matter, $a_{\mathrm{N}}$. The acceleration $a$ differs from $a_{\mathrm{N}}$ only when $a_{\mathrm{N}}$ is lower than about $a_0 = 1.35^{+0.28}_{-0.42} \times 10^{-8}$ cm s$^{-2}$ (Famaey et al. 2007). This functional dependence has been tested many times (see the review by Famaey & McGaugh, 2012), mainly in the late-type galaxies (LTGs, i.e. the spiral galaxies). Indeed, observations show that the relation between $a$ and $a_{\mathrm{N}}$ (the acceleration relation, AR) has a very low scatter for the LTGs independently of their properties or environment. The best available observations of the LTGs are consistent with no intrinsic scatter in the AR (McGaugh et al. 2016), as expected by MOND. The tightness of the AR for the LTGs remains unexplained with the DM hypothesis.

Investigations of the AR in the early-type galaxies (ETGs, i.e. the elliptical and lenticular galaxies) is much less advanced. These galaxies typically lack the disks of rotating gas that enable measuring the rotational velocity, and hence the acceleration $a$, in the LTGs up to large radii. There are ways to investigate the gravitational fields near the ETG centers, such as from the velocity dispersion profiles of stars or from the temperature and luminosity profiles of the hot gas coronas. These measurements are however available only in the regions where the acceleration $a$ is high compared to break acceleration $a_0$. To probe the weak gravitational field at the outskirts of the ETGs, we can rely, more or less, only on the Jeans analysis of the tracers such as planetary nebulae and globular clusters (GCs) (see, e.g. Samurović 2007). With this method, we are looking for an analytical profile of the gravitational field of the galaxy that can explain the observed velocity-dispersion profiles of the GCs. This method requires measuring radial velocities of many GCs that have to be obtained by very time consuming observations at large telescopes. This is the reason why the number of the ETGs studied using the Jeans analysis slowly increases.

Here we study using the Jeans analysis the gravitational field profiles up to 5 effective radii ($R_{\mathrm{e}}$) for 15 ETGs, which is close to the largest sample possible today. We use these profiles to investigate the AR in ETGs in unprecedented detail. We find that only 4 or 5 of our ETGs follow the same AR as the LTGs.

## 2. OBSERVATIONAL DATA

The ETGs in our sample are objects with a wide range of luminosities, morphologies and environments (field, group and cluster galaxies). We used observational data from several sources that will be listed in our prepared paper (most of them came from Pota et al. 2013). We work with a *total* sample of GCs for each galaxy (not splitting into red and blue sub- populations) in order to have more clusters per bin because our goal is to determine as accurately as possible the velocity dispersion and departures of the GC radial velocity distribution from a Gaussian. The table of our ETGs and their properties is presented in these Proceedings (Samurović, invited lecture).

## 3. OUR METHOD

### 3. 1. DYNAMICAL MODELS

For all 15 ETGs in our sample we solve the Jeans equation in a spherical approximation (e.g. Binney & Tremaine 2008). For each galaxy we consider 3 cases of the anisotropy parameter (isotropic, radially and tangentially dominated) as in Samurović

(2014, hereafter S14). We model the gravitational potential of our galaxies as $\phi = \phi_* + \phi_{\mathrm{NFW}}$, where $\phi_*$ is the Newtonian gravitational potential generated by the stars observed in the galaxy and $\phi_{\mathrm{NFW}}$ is the Newtonian potential of an NFW DM halo (Navarro, Frank & White 1997). There are three free parameters: the stellar mass-to-light ratio and the characteristic radius and density of the halo. We substitute $\phi$ in the Jeans equation and find the free parameters so that the deviation of the observed velocity dispersion profile from the velocity dispersion profile given by the Jeans equation is minimized. Such a potential is then adopted as the real gravitational potential of the galaxy.

### 3. 2. BARYONIC MODELS

In order to obtain the acceleration $a_{\mathrm{N}}$, we had to derive the stellar mass-to-light ratio, $M/L_*$, of every galaxy. When it is known and the galaxy is assumed to be spherical, then the acceleration $a_{\mathrm{N}}$ can be calculated from the observed luminosity distribution easily. We used several methods to derive $M/L_*$: 1) From the color index of the galaxy and stellar population synthesis (SPS) models, 2) from the dynamical models as the dynamical mass cumulated under $0.5\,R_{\mathrm{e}}$ divided by the cumulated luminosity under the same radius; this is based on the fact that no DM is usually needed in ETG centers and 3) similarly, we estimate $M/L_*$ from the dynamical mass cumulated below $1\,R_{\mathrm{e}}$.

## 4. RESULTS AND DISCUSSION

The plot below shows the ARs found for the ETGs in our sample. The gray area shows the common AR for the 153 LTGs from McGaugh et al. (2016) where the vertical thickness corresponds to the $\pm 1\,\sigma$ average scatter. We can see that only 4 of our 15 ETGs have their AR common with the AR of the LTGs. They are NGC 821, NGC 1400, NGC 2768 and NGC 3377. This result does not change for any choice of the dynamical or baryonic models discussed above; possibly only NGC 4494 could be added to the four common galaxies.

We note that our ETGs following the AR of the LTGs resemble the LTGs also in other regards (see the aforementioned table): their stellar content is supported more by ordered rotation than velocity dispersion, they have disky isophotes, they sometimes appear very flattened in projection, they have the bluest colors in our sample and avoid galaxy clusters. These facts suggest that their formation history is related to the formation history of the LTGs. They could, for example be spiral galaxies which lose their gas by a starburst. We also note they can be modeled in MOND without additional DM, see S14, Samurović et al. (2014) and also our forthcoming paper. On the other hand, massive ETGs, such as NGC 3115, NGC 4365 and NGC 5846 which deviate significantly from the AR of the LTGs, need copious amounts of DM in their outer regions even in the MOND approach (see S14).

One possibility is that our results exclude MOND. Given its previous success, including in ETGs, our results should be verified for our galaxies by an independent method and the reliability of the Jeans analysis should tested against numerical simulations. It is possible to reconcile MOND with our results by supposing additional invisible matter in the galaxies. MOND is already known to require some DM in galaxy clusters.

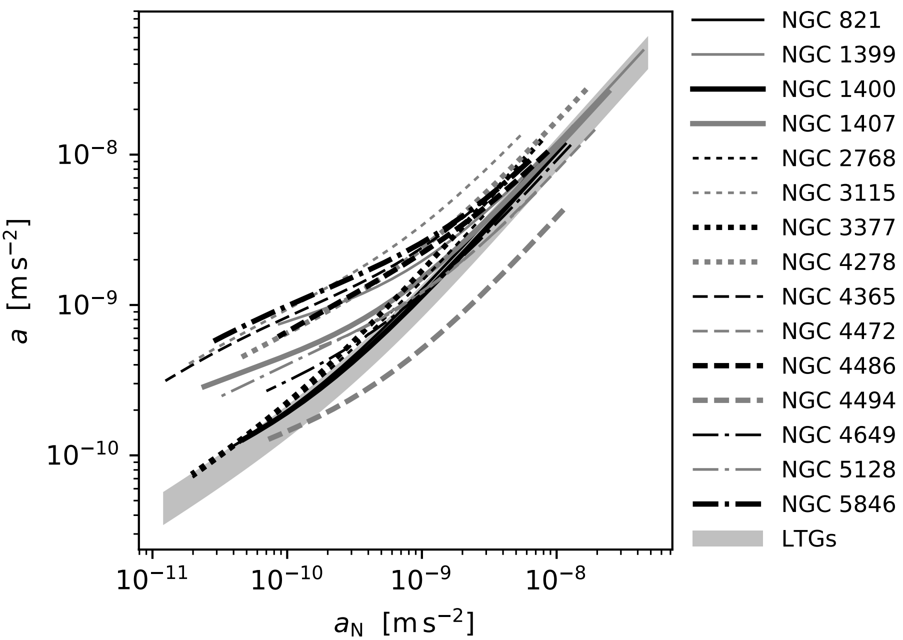


Figure 1: The acceleration relation for the 15 ETGs.

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