Publ. Astron. Obs. Belgrade No. 98 (2018), 329 - 332 *Poster*

DYNAMICAL MODELS OF THREE LENTICULAR GALAXIES: NGC 1023, NGC 3115 AND NGC 4526

S. SAMUROVIĆ

Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
E–mail: srdjan@aob.bg.ac.rs

Abstract. Lenticular galaxies (S0s) together with elliptical galaxies belong to the class of early-type galaxies (ETGs). The main features of S0s are a visible disk component and a prominent bulge component. In this contribution we study the kinematics and dynamics of three S0 galaxies which possess globular clusters (GCs) which extend beyond approximately five effective radii. We analyze NGC 1023, NGC 3115 and NGC 4526 based on their GCs. We use the kinematics of these galaxies which we extracted in order to construct the dynamical models of these objects. We use the Jeans equation based on both Newtonian and MOND methodologies. In the Newtonian case we use mass-follows-light assumption and we also test the models with dark matter (DM) in the Navarro-Frenk-White form. We find that while NGC 1023 does not need a significant amount of DM, for the remaining two galaxies, NGC 3115 and NGC 4526 the dark component fully dominates stellar matter. Three MOND models that we tested show that while NGC 1023 can be modeled without DM in MOND, for NGC 4526 there is a hint of an additional dark component and NGC 3115 needs a significant amount of DM in its outer parts. Finally, we compare our findings with the predictions of the Λ cold dark matter cosmology.

1. INTRODUCTION

The problem of the contribution of dark matter (DM) in the total dynamical mass of various types of galaxies remains one of the most important unsolved question of the contemporary astronomy. The fact that DM dominates the mass of spiral galaxies is well-known, although, very recently, the discovery that the rotation curves for the outer disks of six massive star-forming galaxies at redshifts z between approximately 0.6 and 2.6 are not constant, as observed in the local Universe, but decrease with radius (Genzel et al. 2017). This new finding may suggest the lack of DM in spirals beyond the local (low-redshift) Universe. As for the problem of DM in the other class of galaxies, early-type galaxies (ETGs, made of ellipticals and lenticulars), in the local Universe, the situation is more complex. More than 10 years ago, in at least in some galaxies (see e.g. Samurović and Danziger 2005) the lack of DM in these objects was detected. This has led to the intense observational and theoretical works which suggest that the situation is not simple; there possibly exist two classes of ETGs, one in which the DM content is negligible and the other in which DM dominates the visible, stellar, matter in the outer parts of these galaxies (see e.g. Samurović 2014, hereafter S14). An important obstacle in the analysis of DM in ETGs is the fact that the detection of DM there is much more complicated than in the case of their spiral counterparts. ETGs lack cool gas in most cases and the usage of 21-cm observations to trace kinematics of neutral hydrogen is not feasible. Therefore, different techniques were tested and other methodologies were used in order to measure the total dynamical mass out to large galactocentric radii in ETGs. This is especially important because DM is expected to dominate luminous matter there, i.e. beyond $2-3$ effective radii (R_e). We described various observational techniques and the theoretical approaches for the study of DM in ETGs in Samurović (2007) and the update is provided in S14. In this contribution we employ both methodologies, Newtonian and MOND (Modified Newtonian Dynamics, Milgrom 1983).

Here, we rely on globular clusters (GCs) which are a very useful tool in the study of DM in ETGs and the reconstruction of the evolutionary history of galaxies in the local Universe. They extend out to several R_e. In S14 we used a sample of 10 ETGs coming from the SLUGGS (SAGES Legacy Unifying Globulars and Galaxies Survey, where SAGES is the Study of the Astrophysics of Globular Clusters in Extragalactic Systems) sample of Pota et al. (2013) as tracers of the gravitational potential in both the Newtonian (mass-follows-light and DM models) and the MOND approaches. We found that Newtonian mass-follows-light models without a significant amount of DM can provide successful fits for only one galaxy (NGC 2768) whereas the remaining nine ETGs require various amounts of DM in their outer parts (beyond $2-3R_e$); in the same paper various MOND models were also studied and it was found that MOND alone is not sufficient to fully explain the dynamics of six galaxies in the sample. Only one of the galaxies in S14 was a lenticular galaxy (S0), NGC 3115, and this object will be presented below. The additional two S0 galaxies come from our recent paper (Samurović 2017, hereafter S17): NGC 1023 and NGC 4526.

2. OBSERVATIONAL DATA

In this contribution we will analyze three S0 galaxies with GCs taken from the SLUGGS database (see S14 an S17 for references). The SLUGGS survey uses the combination of Subaru/Suprime-Cam wide-field imaging with spectra from the Keck/DEep Imaging Multi-Object Spectrograph (DEIMOS) multi-object spectrograph. We extract full kinematic profiles out to several effective radii: we determine the velocity dispersion and the symmetric and asymmeteric departures from the Gaussian distribution of their GC radial velocities.

2. 1. NGC 1023

NGC 1023 is a lenticular galaxy at the distance $D = 11.1$ Mpc which means that $1' \approx 3.23$ kpc and $1'' \approx 53.83$ pc. The effective radius is $R_e = 48$ arcsec and the systemic velocity is $v_{\rm sys} = 602$ km s^{-1}. The Sérsic index used in dynamical models is $n_* = 4.2$. The absolute B-band magnitude of NGC 1023, $M_B = -20.61$ and its total apparent corrected $B-V$ color is equal to 0.91 (from the HyperLeda database). We used 113 GCs belonging to NGC 1023 in our dynamical analysis and the slope of their GCs ($N \propto R^{-\gamma}$) is $\gamma = 1.416$. The rotational velocity of GCs is $v_{\rm rot} = 119$ km s^{-1}.

2. 2. NGC 3115

NGC 3115 is a S0 galaxy and is found at the distance $D = 9.4$ Mpc which means that $1' \approx 2.74$ kpc and $1'' \approx 45.59$ pc. The effective radius is $R_e = 85$ arcsec and the systemic velocity is $v_{\rm sys} = 663$ km s^{-1}. The Sérsic index is $n_* = 4.4$ and the absolute B-band magnitude of NGC 3115, $M_B = -19.94$. Its total apparent corrected $B-V$ color is equal to 0.89 (from the HyperLeda database). We used 150 GCs belonging to NGC 3115 in our dynamical analysis and two different slopes were used in our dynamical models, $\gamma_{\rm in} = 1.34$ in the inner region, interior to $\sim 2R_e$ and $\gamma_{\rm out} = 4.17$ in the outer region, beyond $\sim 2R_e$ (see S14 for details). The rotational velocity of GCs is $v_{\rm rot} = 100$ km s^{-1}.

2. 3. NGC 4526

NGC 4526 is a S0 galaxy and is found at the distance $D = 16.4$ Mpc which means that $1' \approx 4.77$ kpc and $1'' \approx 79.54$ pc. The effective radius is $R_e = 32.4$ arcsec and the systemic velocity is $v_{\rm sys} = 617$ km s^{-1}. The Sérsic index is $n_* = 3.6$ and the absolute B-band magnitude of NGC 4526, $M_B = -20.48$. Its total apparent corrected $B-V$ color is equal to 0.98 (from the HyperLeda database). 107 GCs belonging to NGC 1023 were used in our dynamical analysis and the slope of their GCs is $\gamma = 1.420$. The rotational velocity of GCs is $v_{\rm rot} = 142$ km s^{-1}.

3. DYNAMICAL MODELS

For all three S0 galaxies we solve the Jeans equation (e.g. Binney & Tremaine 2008) in a spherical approximation for both abovementioned approaches, Newtonian and MOND:

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

where $a_{\rm N;M}$ is an acceleration term which is different for each approach: in the Newtonian ('N') approach it is equal to $a_{\rm N} = -GM(r)/r^2$ and for MOND ('M'), $a_{\rm M}$ satisfies (Milgrom 1983): $a_{\rm M}\ \mu\left(\frac{a_{\rm M}}{a_0}\right) = a_{\rm N}$. In eq. 1, σ_r is the radial stellar velocity dispersion, $\alpha = {\rm d}\ln\nu/{\rm d}\ln r$ is the slope of tracer density ν. More details are available in S14.

The non-spherical nature of the GC dispersion is expressed through the following well-known equation, $\beta = 1 - \frac{\overline{v_\theta^2}}{\sigma_r^2},$. Three different cases of β were tested (purely isotropic case, radially and tangentially anisotropic cases) and the details are given in S14 and S17. The rotation and the dispersion profile are both folded into a root mean square velocity profile $v_{\rm rms} = \sqrt{v_{\rm rot}^2 + \sigma^2}$ where $v_{\rm rot}$ is the rotation velocity of each S0 galaxy studied here and σ is the dispersion. As can be seen above (Sections 2.1-2.3) all three S0 galaxies have non-negligible rotational velocities ($v_{\rm rot} \geq 100$ km s^{-1}).

4. 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 and DM is added to the stellar component in the form of an NFW (Navarro, Frank & White 1997) DM halo (see S14 and S17 for details). We also tested several MOND models using the Jeans equation in the spherical approximation, the "simple" MOND formula, the "standard" formula and the "toy" formula. The expressions and references are given in S14. The best-fit values for each tested model (all three cases of anisotropy were tested for all three S0 galaxies) are compared with the estimates coming from several stellar population synthesis (SPS) models (see S14 and S17 for details). Also, in S14 and S17 the details about the best-fitting NFW models are presented.

To summarize, we here used GCs as a tracer of the potential of three S0 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 conclusions are:

- We found that NGC 1023 does not need a significant amount of DM. On the other hand, for NGC 3115 and NGC 4526 the dark component completely dominates visible matter (for NGC 3115 even in the inner regions). The NFW models provided good fits for all three S0 galaxies. If one plots the concentration parameter of each galaxy as a function the virial mass one can see that while NGC 1023 and NGC 4526 can be found in the region predicted by the ΛCDM cosmology, the galaxy NGC 3115 has a very large concentration parameter inconsistent with its virial mass (see Fig. 8 in S17).

- We also solved the Jeans equation in the spherical approximation for three different MOND models (standard, simple and toy) and found that while for NGC 1023 all three MOND models can successfully fit the velocity dispersion without DM, both NGC 3115 and NGC 4526 need DM even using the MOND approach, although for NGC 4526 there is a hint that MOND can fit the velocity dispersion throughout the whole galaxy.

Acknowledgment

This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia through project no. 176021, "Visible and Invisible Matter in Nearby Galaxies: Theory and Observations". The author thanks the referee, Dr. Luka Č. Popović, for his useful comments.

References

Binney, J. J. & Tremaine, S.: 2008, Galactic Dynamics, 2nd Ed., Princeton University Press.
Genzel, R., Förster Schreiber, N. M., Übler, H. et al.: 2017, *Nature*, **543**, Issue 7645, 397.
Milgrom, M.: 1983, *Astrophys. J.*, **270**, 365.
Navarro, J. F., Frenk, C. S. & White, S. D. M.: 1997, *Astrophys. J.*, **490**, 493.
Pota, V. et al.: 2013, *Mon. Not. R. Astron. Soc.*, **428**, 389.
Samurović, S.: 2007, Dark Matter in Elliptical Galaxies, *Publications of the Astronomical Observatory of Belgrade*, No. 81.
Samurović, S.: 2014, *Astron. Astrophys.*, **570**, A132, 29 pp. (S14).
Samurović, S.: 2017, *Serb. Astron. J.*, **195**, 9 (S17).
Samurović, S. & Danziger, I. J.: 2005, *Mon. Not. R. Astron. Soc.*, **363**, 769.