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VISIBLE AND INVISIBLE MATTER IN NEARBY GALAXIES: THEORY AND OBSERVATIONS

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Abstract. We describe the main accomplishments of the project "Visible and Invisible Matter in Nearby Galaxies: Theory and Observations" (no. 176021) funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia. We have studied both visible (stars, gas, dust) and invisible (dark) matter in nearby galaxies of various morphological types. One of the main tasks of the project was to define the sample which includes both early- (elliptical) and late- (spiral) type galaxies and this was accomplished successfully. The galaxies from our sample were studied using their photometric and spectroscopic (also radio) data that come from available catalogs and databases. We studied in detail their kinematics and dynamics and we analyzed the anisotropies in stellar motions. We decomposed photometric profiles to discover various structures in those objects. Dark matter was especially analyzed in the case of elliptical galaxies using various observational techniques and theoretical approaches. This project also included several sub-projects, where the most important one was dedicated to the purchase and the construction of the 1.40 m telescope "Milanković" mounted at the Vidojevica Astronomical Station. The remaining three sub-projects include the work on i) the Galactic habitable zone and its features connected with the kinematics and dynamics of the Milky Way and nearby spiral galaxies, ii) blazars and iii) cosmological simulations related to supermassive black holes, massive and dwarf galaxies and semi-analytic analysis of cosmological simulations.

1. INTRODUCTION

Project "Visible and Invisible Matter in Nearby Galaxies: Theory and Observations" (no. 176021) funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia (MESTDRS) gathered 24 researchers from 5 institutes: the Astronomical Observatory Belgrade (AOB), the Faculty of Mathematics (University of Belgrade), the Institute of Physics (Belgrade), the Faculty of Natural Sciences (University of Niš) and the Faculty of Electronics (University of Niš). The project was ranked 8th of 435 submitted basic research projects after the call of the MESTDRS (then Ministry of Science and Technological Development) in 2010 and has been led from the beginning (2011) by the author of this contribution. The following researchers took part in the realization of the project from the beginning to this conference: Dr. Srdjan Samurović, Dr. Milan Ćirković, Dr. Branislav Vukotić, Dr. Ana Vudragović (née Lalović), Dr. Oliver Vince, Dr. Ištvan Vince, Dr. Attila Cséki, Dr. Milan Bogosavljević, Dr. Zoran Knežević, Dr. Zorica Cvetković, Dr. Rade

Pavlović, Dr. Nemanja Martinović, Milena Jovanović, Dr. Miroslav Mićić, Dr. Milica Mićić, Dr. Majda Smole, Ana Mitrašinović (AOB), Prof. Dr. Olga Atanacković (Department of Astronomy, Faculty of Mathematics, University of Belgrade), Dr. Dragan Lukić (Institute of Physics, Belgrade), Prof. Dr. Goran Djordjević, Prof. Dr. Ljubiša Nešić, Dr. Milan Milošević (Faculty of Sciences and Mathematics, University of Niš), Prof. Dr. Goran Djordjević and Darko Todorović (Faculty of Electronics, University of Niš). During the realization of the project four PhD theses related to the project were defended (A. Vudragović, M. Milošević, M. Smole and N. Martinović, see these Proceedings for the details) and 2 more PhD theses are near completion (M. Jovanović and A. Mitrašinović). Between 2011 and 2016 the participants published 76 refereed papers related to the project in various journals and also numerous contributions in various books of proceedings.

From the very beginning of the work of the project special attention was given to the sub-project (led by Dr. Milan Bogosavljević) related to the construction and mounting of the 1.40 m telescope "Milanković" and the most important details regarding these activities will be presented below. Additional 3 sub-projects were launched over the course of the project and will also be described below.

This contribution will necessarily, due to a limited available space, present a condensed description of the research performed within project "Visible and Invisible Matter in Nearby Galaxies: Theory and Observations". The reader is referred to the papers listed in the reference list at the end as well as to the contributions at the Serbian Astronomical Conference by the participants of the project.[1]

2. THE "MILANKOVIĆ" TELESCOPE

From the very beginning of the project we began to work on the selection of the optimal configuration of the 1.50 m-class telescope to be purchased and mounted at the top of Vidojevica and the decision was made to name it "Milanković" after the famous Serbian astronomer. The activities related to the construction and procurement of the "Milanković" telescope were synchronized with activities of the BELISSIMA (BELgrade Initiative for Space Science, Instrumentation and Modelling in Astrophysics, call FP7-REGPOT-2010-5, contract no. 256772) project. We described the activities related to the procurement earlier (see Samurović 2016c, 2017a) and here only the most important information is presented.

The 1.40 m "Milanković" telescope was produced by the reputable Austrian company ASA (AstroSysteme Austria GmbH) using the optics from another eminent company, LOMO, from the Russian Federation. See the details about the final stages of the procurement and the features of the telescope in Samurović et al. (2018). The telescope has been used for various observations and some were part of the project described in that contribution (see below). The extensive tests proved that both the mechanics and the optics were of excellent quality. The telescope was delivered to the Astronomical Station Vidojevica (ASV) on 28 April 2016 when the mounting procedure started and was completed several days later. After some adjustments that were completed at the beginning of June 2016 the first light was taken on 7 June 2016. The image is shown in Samurović et al. (2018, see Fig. 2 there) and we refer the

[1]Note that all contributions in these Proceedings made within project no. 176021 can be traced through the acknowledgment sections present at the end of each paper printed in this volume.

reader to that contribution for more details regarding the present situation (detectors, observational projects) with the "Milanković" telescope. See also two contributions by Vince et al. (2018a,b).

The funds for the telescope were provided by the European Commission through BELISSIMA (76 %) and Serbian MESTDRS (24 %). The MESTDRS provided the funds for the construction of the temporary pavilion where the telescope is currently mounted and the future professional pavilion where the telescope will be mounted in spring 2018. At the time of this writing (late November 2017) the construction works on the building of the new pavilion have been successfully completed and the dome for the new pavilion is currently in the final stages of production by the reputable Italian company Gambato.

The significant help and efforts in the realization of all the activities related to the "Milanković" telescope and its pavilions were provided by Dr. Zoran Knežević and Dr. Gojko Djurašević in their role as Director of the AOB.

3. THE STUDY OF THE VISIBLE MATTER IN NEARBY GALAXIES

We studied the visible matter in nearby galaxies: we analyze both late-type galaxies (hereafter LTGs, i.e. spirals) and early-type galaxies (hereafter ETGs, i.e. ellipticals and lenticulars) using various archives and also the "Milanković" telescope. We constructed the reliable sample of nearby galaxies. Here, some of the most important details are provided and the reader is referred to Vudragović (2018) and also to the paper by Vudragović, Samurović & Jovanović (2016) for more details and relevant references. We used $\alpha.40$ catalog that is cross-matched with the Sloan Digital Sky Survey (SDSS DR7) spectroscopic catalog and the Galaxy Evolution Explorer (GALEX GR6), Two Micron All Sky Survey (2MASS XSC) to add a multiwavelength photometry to the radio and optical spectroscopy originally provided with the $\alpha.40$ catalog. Our final sample has 2180 galaxies and it has radio and optical spectroscopy and photometry from the ultraviolet, through the optical to the near-infrared passband. The morphological distribution of galaxies in our sample suggests that we have about 1/3 of ETGs: the ratio 1:3 reflects the contribution of ETGs to the galaxy population in the local Universe. The remaining fraction (2/3) of the galaxies in the sample are LTGs. For all the galaxies in our sample the following quantities were measured: the velocity dispersions, the Gauss-Hermite coefficients (h_3 and h_4) which describe departures (asymmetric and symmetric) from the Gaussian function, the Sersic indices and the effective radii (R_e) in order to calculate dynamical mass of the galaxies. This is most probably the largest available sample of galaxies for which the kinematics of the inner regions analyzed includes the departures from the Gaussian. We have also measured the Lick indices important for the estimates of ages and metallicities of the galaxies in our sample. In the study of the kinematics of the nearby galaxies we relied on two stellar libraries: the synthetic library based on the empirical library STELIB (with 39 template stars) and the empirical library which is Elodie low resolution stellar library (with 998 template stars). Regarding the analysis of the stellar spectra, we mention here one important result: we studied the distribution of the h_4 parameter and we found that there is an increase of its value going from LTGs to ETGs, which means that in ETGs the radial orbits dominate (see Figs. 13 and 14 in Vudragović et al. 2016). We used various statistical tests on the h_4 distribution and compared various morphological types. We found that the distribution of early-type vs. late-type and Sab vs. Scd galaxies do not come from the same distribution, whereas when ellipticals are confronted with lenticulars, we have a hint that they come from the same distribution; this may mean that they share the similar formation scenario thus leading to an interesting constraint important for models of galaxy evolution.

In our study of dark matter (hereafter, DM, see below) we needed to estimate the contribution of the visible, stellar, component. In Samurović, Vudragović & Jovanović (2015) we analyzed the massive spiral galaxy NGC 2841 and we took into account predictions from various stellar population synthesis (SPS) models based on different initial mass function (IMFs). Various SPS models were also used when we analyzed the problem of the contribution of DM in ETGs. In the case of spiral galaxies we also analyzed their photometry. In the case of the aforementioned NGC 2841 in the attempt of the decomposition of its surface brightness profile we first relied on the archival data (Samurović et al. 2015) and recently, we used the "Milanković" telescope to obtain the deep near-infrared photometry (I-band), see Vudragović et al. (2018). More details about the use of photometry on our sample is available in Vudragović (2018).

4. DARK MATTER IN EARLY-TYPE GALAXIES

One of the main research topic of the project is the study of DM in ETGs. Here, it is important to note that ETGs are studied to a lesser degree than their spiral counterparts. The following list includes some of the most important reasons for such a situation: i) there is a lack of cool gas in early-types necessary for obtaining rotation curves, ii) ETGs are faint in their outer parts, which require long exposures to obtain high quality spectra and iii) there is no accurate knowledge of the shape of orbits in these galaxies which leads to the mass-anisotropy degeneracy (see e.g. Samurović 2007). For the study of the DM problem one can rely on different studies: one can analyze long-slit and/or integral field unit (IFU) spectra which is related to the study of the contribution of the visible (i.e. stellar) component to the total dynamical mass, one can study the kinematics of various tracers of the total dynamical mass such as planetary nebulae (PNe) and globular clusters (GCs), one can study the X-rays in ETGs and one can rely on gravitation lensing when studying DM in ETGs.

In the project no. 176021 we studied different aspects of DM in ETGs. We used two different methodologies to study several ETGs out to several effective radii: Newtonian (mass-follows-light and DM models) and the MOND (MOdified Newtonian Dynamics). From the beginning of project no. 176021 we analyzed the following ETGs: NGC 4472 (M 49) in Samurović (2012), NGC 821 in Samurović et al. (2014), NGC 1400, NGC 1407, NGC 2768, NGC 3115, NGC 3377, NGC 4278, NGC 4365, NGC 4486, NGC 4494 and NGC 5846 in Samurović (2014, hereafter S14), NGC 1399 in Samurović (2016a), NGC 5128 in Samurović (2016b) and NGC 1023 and NGC 4526 in Samurović (2017b); see also Samurović (2018). For all the galaxies we use GCs as a tracer of the gravitational potential and also rely on the PNe data, where available. We use the radial velocities of the GCs in ETGs and we extract the full kinematical profiles of our galaxies out to several effective radii: the velocity dispersion and s_3 and s_4 parameters which describe asymmetric and symmetric departures from the Gaussian (analogous to h_3 and h_4 parameters mentioned above). We did not split the GCs of each galaxy into blue and red population and work with a *total* sample of GCs for each galaxy in order to have more clusters per bin because our goal is to

Table 1: The list of ETGs used in the analysis of Bílek & Samurović (2018). Columns are as follows (the references will be available in our forthcoming paper). (1): name of the galaxy. (2): distance to the galaxy in Mpc. (3): B-band absolute magnitude. (4): morphological type. (5): environment of each galaxy (”G” means that the galaxy belongs to a group, ”F” is a field galaxy and ”C” means that the galaxy belongs to a cluster). (6) central rotator type (”s” indicates slow and ”f” indicates slow rotators). (7): isophotes (”D” are disky isophotes, ”B” are boxy isophotes and ”0” are pure ellipses) (8): corrected $B - V$ colors. The objects for which the names are given in italics follow the AR of the LTGs.

name (1)	D[Mpc] (2)	M_B (3)	Type (4)	Env (5)	Rot (6)	Iso (7)	$B - V$ (8)
NGC 0821	23.4	-20.82	E6	F	f	D	0.87
NGC 1399	19.0	-20.81	E1pec	C	s	D	0.93
NGC 1400	26.8	-20.35	S0/E0	G	f	0	0.89
NGC 1407	26.8	-21.49	E0	G	s	0	0.95
NGC 2768	21.8	-21.26	E6/S0_1/2	G	f	D	0.91
NGC 3115	9.4	-19.94	S0	F	f	D	0.90
NGC 3377	10.9	-19.32	E6	G	f	D	0.82
NGC 4278	15.6	-19.50	E1-2	G	f	B	0.90
NGC 4365	23.3	-21.00	E3	G	s	B	0.93
NGC 4472	16.7	-21.71	E2	C	s	B	0.93
NGC 4486	17.2	-22.05	E0	C	s	B	0.92
NGC 4494	16.6	-21.07	E1-E2	G	f	D	0.85
NGC 4649	17.3	-21.59	E2/S0	C	f	B	0.93
NGC 5128	3.8	-20.55	S0pec(Epec)	G	f	?	0.87
NGC 5846	24.2	-21.34	E0	G	s	B	0.94

determine as accurately as possible the velocity dispersion and departures of the GC radial velocity distribution from a Gaussian.

The procedure of solving of the Jeans equation (e.g. Binney & Tremaine 2008) in a spherical approximation for both Newtonian and MOND approaches is given in S14. The fact that there exists the mass/anisotropy degeneracy is one of the main problems for the Jeans analysis: for all ETGs from our sample we calculated the departures from the Gaussian and in our dynamical models we analyze isotropic case, tangentiallly dominated case and radially dominated case based on numerical simulations. In all our dynamical models we fit the velocity dispersion profies of ETGs.

In establishing the amount of DM in ETGs we relied on various SPS models: we used seven different models with several IMFs (see S14 for more details). For the sake of brevity, we will here describe only the major findings from S14 and the reader is referred to the papers mentioned above for more details regarding individual ETGs. S14 is the work with the largest number of galaxies simultaneously analyzed in Newtonian and MOND approaches. We found that only one out of ten ETGs can be modeled with a single value of the constant mass-to-light ratio that is approximately consistent with the value of the stellar component, NGC 2768, showing the lack of significant amount of DM. Three more galaxies (NGC 1400, NGC 3377, and NGC 4494) show an increase of the total mass-to-light ratio with radius between the innermost and outermost radii, which suggests the existence of DM in them. The object NGC 4486 is the only galaxy that needs significant amount of DM in its inner region. When we solved the Jeans equation in the spherical approximation for three different MOND models (standard, simple and toy) we discovered that the standard model required the largest mass-to-light ratio while the toy MOND model required the smallest. We found that only few ETGs could be modeled with a mass-to-light ratio consistent with the no-DM hypothesis, assuming the values of the mass-to-light ratios that are consistent with the stellar mass only: NGC 1400, NGC 2768, NGC 3377, and NGC 4494. In the case of NGC 4486 we found that it requires DM in MOND even in its inner region (interior to $\sim 0.35R_{\mathrm{e}}$). 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 $\sim 3R_{\mathrm{e}}$, and NGC 4365 and NGC 4486 require DM beyond $\sim 1R_{\mathrm{e}}$ and $\sim 0.35R_{\mathrm{e}}$, respectively. Thus we reached the conclusion that in the MOND modeling of the ETGs in the sample some galaxies can be fitted with the visible matter only, whereas, in some cases, the additional dark component is needed. This represents the problem for MOND which is based on one free parameter only (mass-to-light ratio). The important conclusion that we obtained is the fact that the MOND approach cannot provide a successful fit for ETGs that are slow rotators.

In Bílek & Samurović (2018) we analyzed the sample of 15 ETGs and our focus is 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 LTGs, in agreement with the MOND. The reader is referred to that contribution and in Table 1 we present the most important details for the ETGs of our sample: the galaxies listed are objects with a wide range of luminosities, morphological types (within the early-type class) and belong to different environments (from field galaxies to members of groups and clusters).

5. DARK MATTER IN SPIRAL GALAXIES

At the very beginning of the project the kinematics of the Milky Way was studied using the measurements of the radial velocities of the blue horizontal branch (BHB) halo stars: the predictions of Newtonian gravity and different MOND models were tested, taking orbital anisotropies into account. We used halo stars of our Galaxy as a tracer of its gravitational potential and then we solved the Jeans equation for both the Newtonian and the MOND approaches. In the Newtonian approach we found that the truncated flat model with DM can provide good fit to the observed velocity dispersion, whereas for the MOND models we found that two models can provide a fit to the data without significant anisotropies whereas two other tested models need various anisotropies to obtain the same result (see Samurović & Lalović 2011 for details about the models).

In our work from 2015 we analyzed in detail the dynamical models of the massive spiral galaxy NGC 2841 using both the Newtonian models with Navarro-Frenk-White (NFW) and isothermal dark haloes, as well as various MOND models (Samurović et al. 2015). We relied on the observations coming from several publicly available data bases and we used radio data, near-infrared photometry as well as spectroscopic observations and found that both tested Newtonian DM approaches can successfully fit the observed rotational curve of NGC 2841. We again (as in the case of ETGs, see above) used three MOND models (standard, simple and, for the first time in the literature applied to another spiral galaxy than the Milky Way, Bekenstein's toy model). We found that the best result was obtained with the standard MOND model. It is interesting to note that we found that the best-fitting NFW model is inconsistent with the predictions of the cold dark matter (CDM) cosmology, because the inferred concentration index is too high for the established virial mass (see Fig. 10 of Samurović et al. 2015).

In the recent paper Jovanović (2017) analyzed the dynamical models for two galaxies, the massive spiral galaxy NGC 5055 and the dwarf irregular DDO 154. She used THINGS (The HI Nearby Galaxy Survey) HI observations to determine the rotation curves of the two galaxies and gas contributions, and Spitzer Survey of Stellar Structure in Galaxies (S4G) photometric observations in the 3.6 μm band to decompose the surface brightness profiles of the galaxies. Jovanović (2017) studied NFW and isothermal halo models for the DM distribution, together with the most recent and reliable radio observations of HI to determine the rotation curves of these galaxies taking into account the contributions from the neutral gas and the luminous matter. Jovanović (2017) found that the isothermal DM model successfully fitted both observed rotation curves with realistic values for stellar mass-to-light ratio, while the NFW model needed further constraints for mass-to-light ratio to fit the rotation curve of DDO 154.

6. NUMERICAL SIMULATIONS OF THE EVOLUTION OF GALAXIES AND SUPERMASSIVE BLACK HOLES

Within this sub-project (active from 2013, led by Dr. Miroslav Mićić) various numerical simulations were performed at the Institute of Physics (also, the Millennium and Millennium-II simulations were used). The following phenomena were studied: elliptical galaxy formation using the activity of supermassive black holes (SMBHs) in their centres, evolution of dwarf galaxies in clusters of galaxies and formation of SMBHs and role of galaxy mergers in their evolution. The list of references includes: Smole, Mićić & Martinović (2015), Mićić, Martinović & Sinha (2016) and Martinović & Mićić (2017); see also Martinović & Mićić (2018), Smole et al. (2018), Mitrašinović et al. (2018) and, Milošević et al. (2018).

7. STUDY OF BLAZARS

The goal of this sub-project (active from 2014, led by Dr. O. Vince) is to study the origin and physics of high flux variability in all spectral domains using multi-wavelength observarions. The recent results of optical-to-radio monitoring of the blazar CTA 102 by the Whole Earth Blazar Telescope Collaboration show that the observed long-term flux and spectral variability is best explained by an inhomogeneous, curved jet that undergoes orientation changes. The work within this sub-project was done in collaboration with the researchers from Italy (Astrophysical Observatory of Torino) and Bulgaria (Bulgarian National Astronomical Observatory). Telescope "Milanković" was used and will continue to be used for the study of blazars, using both photometry and spectroscopy (see Vince et al. 2018b). Some of the most recent references include: Gupta et al. (2017) and Raiteri et al. (2017).

8. GALACTIC HABITABILITY: NUMERICAL SIMULATIONS AND BASIC QUESTIONS

The main research goal of this sub-project (active from 2015, led by Dr. B. Vukotić) was to investigate the history of galactic habitability and relevant time scales. Special attention was given to the influence of dynamics of matter in the Galactic disk to Milky Way habitability. The most important result so far is that the analysis of snapshots from the N-body simulation of an isolated Milky Way-like galaxy points that the galactic regions with the highest habitability potential lies in the outskirts of the Galactic disk at galactocentric distances in excess of 10 kpc. In a separate work it was argued that the life-threatening risk of radiation from energetic explosions (such as γ-ray bursts) can be mitigated by sufficiently advanced technological societies using swarm shields constructed from stellar system small bodies. The related results are presented in two research papers (Ćirković & Vukotić 2016; Vukotić et al. 2016). Also, an overview of using N-body simulations as a novel tool to investigate galactic habitability is presented in a book chapter (Vukotić 2017); see also Djošović, Vukotić & Ćirković (2018).

9. THEORETICAL COSMOLOGY

The group of researchers from the Faculty of Sciences and Mathematics, University of Niš led by Prof. Dr. Goran Djordjević studied various theoretical aspects of modern cosmology, such as braneworld cosmology and theory of inflation. They also organized a network of international collaborations with the ICTP from Trieste and CERN through SEENET-MTP (Southeastern European Network in Mathematical and Theoretical Physics). Some recent papers include: Bilić et al. (2017a), Bilić, Domazet & Djordjević (2017b,c).

10. POPULARIZATION ACTIVITIES

The participants of the project took part in education and popularization of astronomy through organization and participation in various meetings and exhibitions, printing of the material related to the popularization of science as well as guests in various radio and TV programs. We here mention only some of the most important meetings (see Samurović 2017a): the BELISSIMA executive meeting, two BELISSIMA workshops, the international BELISSIMA conference and the Serbian-Italian Astronomical Workshop, held in October 2017, after the Serbian Astronomical Conference. Within the activities within the BELISSIMA projects, six episodes of TV programme dedicated to the popularization of astronomy and the presentation of the AOB and "Milanković" telescope were filmed: 4 episodes are present in the BELISSIMA multimedia DVD and the last two ones dedicated to the ASV, telescope "Milanković" and future observational project are available at the BELISSIMA Web site[2].

[2] `http://belissima.aob.rs`

Special attention was given to present the material of interest for foreign spectators and thus some episodes are subtitled in English. See also Atanacković (2018).

11. CONCLUSIONS

In this contribution we briefly presented the most important results of the national project "Visible and Invisible Matter in Nearby Galaxies: Theory and Observations" (no. 176021) active at the AOB from 2011. We have studied the visible matter in various types of galaxies represented by the stellar component. We described our contribution to the analysis of the problem of DM in spiral and early-type galaxies using different methodologies, such as Newtonian and MOND. The interesting result based on the study of the nearby early-type galaxies is that while some galaxies show the lack of DM there are numerous examples that DM dominates in their outer parts and in some galaxies the dark component is dominant even in their inner regions. We described the activities of all the sub-projects, especially the activities that led to the successful construction and mounting of the 1.40 m telescope "Milanković" at the Astronomical Station Vidojevica. For the future we plan: to continue and improve the present theoretical and observational work, to mount the "Milanković" telescope in the new pavilion, to procure new detectors for the "Milanković" telescope, to expand and strengthen the existing collaborations and, finally, we intend to include new researchers (experienced researchers, PhD students) in the existing project and in the project that will be launched in the next project cycle of the MESTDRS which is expected to start soon.

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