Publ. Astron. Obs. Belgrade No. 100 (2021), 145 - 152 *Invited Lecture*

THE CENTENARY OF THE JEANS EQUATIONS: DARK MATTER IN MASSIVE EARLY-TYPE GALAXIES

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Abstract. The year 2019 marked the centenary of the publication of the book *Problems of Cosmogony and Stellar Dynamics* by James Jeans in which he summarized the work on dynamics of stellar systems based on his works published from 1915 onwards. We discuss one important application of his work relevant for contemporary galactic research: we analyze the problem of dark matter in massive early-type galaxies (ellipticals and lenticulars) using various available observational data. We show that in these galaxies dark matter does not dominate in the inner regions, but becomes more important beyond three effective radii.

1. INTRODUCTION

The problem of dark matter (DM) and its contribution to the total dynamical mass of various morphological types of galaxies exists since the 1970s. The existence of DM in spiral galaxies is well documented and the studies of their rotation curves (RCs) provided ample evidence for the existence of DM (see e.g., Bertin 2014). The use of available databases, such as the THINGS (The HI Nearby Galaxy Survey) database (Walter et al. 2008) provides the opportunity to study the DM problem in nearby spirals. For example, Jovanović (2017, and also the contribution by Jovanović et al. in this Book of proceedings) analyzed the spiral galaxy NGC 5055, and also dwarf irregular galaxy DDO 154, using THINGS to examine their RCs. The study of the RCs in both objects shows the significant DM contribution.

The details regarding the study of DM in early-type galaxies (hereafter, ETGs) which include ellipticals and lenticulars are provided in Samurović (2007). It is important to note that ETGs are studied to a lesser degree than their spiral counterparts. The reasons for such a situation include the lack of cool gas (neutral hydrogen HI) in ETGs necessary for obtaining RCs at large galactocentric distances. Another observational fact is that ETGs are faint in their outer parts and thus we need long exposures for obtaining high quality spectra and photometric data at large galactocentric distances (at several effective radii, R_e, where 1 R_e is the radius which encompasses half of the total light of the given galaxy). Last but not least, there is the problem of the lack of knowledge of the shape of orbits in these galaxies and this leads to the well-known mass-anisotropy degeneracy.

The Jeans equations proved to be very useful from the very beginning and remain the main tool of the study of the DM problem in ETGs. There are other, arguably more sophisticated, but much more computationally demanding, methods for estimating the total dynamical masses of ETGs and they include the method based on orbit superposition (Schwarzschild 1979) and the made-to-measure modeling based on the distribution functions (Syer & Tremaine 1996). Alternative theories of gravitation such as the MOdified Newtonian Dynamics (MOND; Milgrom 1983) have been applied to ETGs with various degrees of success. In the present paper we discuss Newtonian dynamics only and refer the reader to our work where the application of the Jeans equations to ETGs in MOND was discussed (Samurović 2019).

The plan of the paper is as follows. In Chapter 2 historic background and basic details regarding the Jeans equations are presented. In Chapter 3 the application of the Jeans equations using integrated stellar spectra in ETGs is described. In Chapter 4 other tracers of gravitational potential in ETGs such as planetary nebulae (PNe) and globular clusters (GCs) are discussed. Finally, in Chapter 5 the main conclusions are given and some directions of the future investigation of DM in ETGs are outlined.

2. HISTORIC BACKGROUND AND FOUNDATIONS OF THE JEANS EQUATIONS

Sir James Jeans (1877 – 1946) in a series of his papers (Jeans 1915, 1916a, 1916b) and later in his book *Problems of Cosmogony and Stellar Dynamics*[1] (Jeans 1919) introduced equations which are now known as the Jeans equations. He applied for the first time to stellar systems the equations previously derived by James Clerk Maxwell (Maxwell 1867) related to the equilibria of the collisionless systems. On page 229 of his book Jeans says: “It now appears that, for our present universe[2], the problem of stellar dynamics is the same as the problem of the kinetic theory of gases with the collisions left out. This being so, stellar dynamics is naturally very much simpler than gas-dynamics”. Maxwell already had a set of equations named after him, so the equations applied by Jeans have become the Jeans equations. However, there were discussions in the literature regarding their name. In 1982 Hénon in his brief paper listed seven possible names and the name Maxwell was conspicuously absent: Liouville equation, Boltzmann equation, collisionless Boltzmann equation, Liouville-Boltzmann equation, Jeans equation, equation of continuity and Vlasov equation (Hénon 1982). He suggested that the proper name would be “collisionless Boltzmann equation”. His, as he called it, “plea” to astronomers and physicists was not adopted by the scientific community. Several decades later, Robson et al. (2017) on the 150th anniversary of the Maxwell’s 1867 paper reviewed the Maxwell-Boltzmann formalism and called the equations devised by Maxwell: “Maxwell’s (other) equations”. Thus, Maxwell’s fundamental work related to electromagnetism can be distinguished from his contribution in the field of collisionless systems.

Below some most important steps needed for the derivation of the Jeans equations are presented and the reader is referred to the book by Binney & Tremaine (2008) for the detailed description of the procedure.

It can be assumed that an elliptical galaxy is a collisionless system made of several billion stars and one can operate in the six-dimensional phase-space volume $\mathrm{d}^3\mathbf{x}\mathrm{d}^3\mathbf{v}$ around the position determined with $\mathbf{x}$ and velocity $\mathbf{v}$. The distribution function,

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[1] The book is available at `https://archive.org/details/problemsofcosmog00jeanrich`.

[2] In modern language this corresponds to our Galaxy.

which is a non-negative function, i.e., $f \geq 0$ is then defined. Using Hamilton's equations, the collisionless Boltzmann equation is obtained which can be written in the following form:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{x}} \cdot \frac{\partial f}{\partial \mathbf{v}} = 0, \tag{1}$$

where Φ is the gravitational potential.

Since in a given ETG individual stars cannot be resolved one has to deal with integrated stellar light of the given galaxy which represents the average of the stellar properties of numerous unresolved stars that lie along each line of sight (LOS). We now define line-of-sight velocity distribution (LOSVD, $F(v_{\rm los})$). The fraction of stars contributing to the spectrum of the galaxy which have LOS velocities between $v_{\rm los}$ and $v_{\rm los}$+d$v_{\rm los}$ is given by $F(v_{\rm los})\mathrm{d}v_{\rm los}$. One can model the LOSVD as a truncated Gauss-Hermite series, i.e., as a Gaussian multiplied by a polynomial (van der Marel & Franx 1993):

$$F_{\rm TGH}(v_{\rm los}) \propto e^{-\frac{1}{2}w^2} \left[1 + \sum_{k=3}^{n} h_k H_k(w)\right], \tag{2}$$

where $w \equiv (v_{\rm los} - \bar{v})/\sigma$. We study h_3 (asymmetric) and h_4 (symmetric) departures from the Gaussian and higher values, h_n with $n > 4$, are also possible. If $h_4 < 0$ then tangential orbits dominate and if $h_4 > 0$ then radial orbits dominate. In dynamical models one can vary $\bar{v}$, σ, h_3 and h_4 until convolution of $F_{\rm TGH}$ and stellar template best reproduces the observed galaxy spectrum and if LOSVD is close to Gaussian then $\bar{v}$ and σ will approximately be equal to $\bar{v}_{\rm los}$ and $\sigma_{\rm los}$.

If we integrate Eq. 1 and take into account that $f(\mathbf{x}, \mathbf{v}, t) = 0$ at sufficiently large $\mathbf{v}$, because there are no stars moving infinitely fast, we obtain:

$$\frac{\partial \nu}{\partial t} + \frac{\partial \left(\nu \bar{v}_i\right)}{\partial x_i} = 0, \tag{3}$$

where $\nu(\mathbf{x})$ is the probability per unit volume of finding a given star at the position $\mathbf{x}$, regardless of its velocity $\mathbf{v}$. This is an equation of continuity of probability. The equation analog to the Euler's equation of fluid flow in spherical coordinates can be written as:

$$\frac{\mathrm{d}\sigma_r^2}{\mathrm{d}r} + \sigma_r^2 \frac{(2\beta + \alpha)}{r} = a_{N;M} + \frac{v_{\rm rot}^2}{r}, \tag{4}$$

where σ_r is the radial component of the stellar velocity dispersion, the α parameter is defined as $\alpha = \mathrm{dln}\nu/\mathrm{dln}r$ is the slope of tracer density ν, the so called anisotropy parameter β is equivalent to the h_4–parameter and $v_{\rm rot}$ is the rotational velocity. Equations (3) and (4) are the Jeans equations. Eq. 4 is the form of the Jeans equation most frequently used in the analysis of DM in the literature. It can be applied using both Newtonian ("N") and MOND ("M") methodologies where $a_{N;M}$ is an acceleration term calculated separately for each methodology. In the Newtonian approach the acceleration is equal to $a_N = -\frac{GM(r)}{r^2}$, where $M(r)$ is the mass enclosed at radius r.

It took some time for the application of the Jeans equation to ETGs and one of the earliest examples can be found in the work of Duncan & Wheeler (1980) in which the analysis of the central parts of the elliptical galaxy M87 was performed (the term "collisionless Boltzmann equation" was used for the equation which was solved).

3. INTEGRATED STELLAR SPECTRA

3. 1. LONG-SLIT SPECTRA

The contribution of DM in ETGs was studied using the Jeans equation through the investigation of their integrated stellar spectra. Also, the analysis of the total mass profiles based on X-ray observations was performed where possible. An early work by Binney, Davies & Illingworth (1990) introduced the two-integral (2I) Jeans modeling procedure: three ETGs (NGC 720, NGC 1052 and NGC 4697) were modeled using the observed velocity dispersion profiles obtained from their long-slit spectra. Although the study of DM was not in their focus they posed the fundamental question to be addressed in the study of DM in ETGs, "is the mass-to-light ratio constant?". The same technique was later used in van der Marel, Binney & Davies (1990) on other four ETGs (NGC 3379, NGC 4261, NGC 4278 and NGC 4472), to distances at most equal to $\sim 1\ R_e$. It was found that constant mass-to-light ratios can provide successful fits to the observed velocity dispersion profiles. Carollo et al. (1995) obtained the long-slit spectra of several ETGs beyond $1\ R_e$ and found that 3 out of 4 galaxies in their sample must possess a dark halo.

Samurović & Danziger (2005) used long-slit spectra to study 4 ETGs and the DM contribution inside $\sim 1{-}3\ R_e$. ETGs IC 1459, IC 3370, NGC 3379 and NGC 4105 were analyzed using 2I Jeans models taking into account full LOSVD and the comparison with X-ray observations was made (where available). Significant amounts of DM were not detected. IC 1459, an ETG with a counter-rotating core, showed high values of the h_4–parameter in its outer parts which implied the existence of radial anisotropies there; also, it was found that DM in this galaxy is not dominant interior to $\sim 3\ R_e$.

One of the latest applications of the analysis of long-slit spectra on ETGs can be found in Salinas et al. (2012): the kinematics of the NGC 7507 was studied and it was found that the models without DM provide an excellent fit of the observed data.

3. 2. INTEGRAL FIELD SPECTROSCOPY

The integral field spectroscopy (IFS) is a powerful technique which provides the larger spatial coverage of integrated stellar spectra than the long-slit observations. Below, some of the projects and their main results are listed (see the review of the studies of structure and kinematics if ETGs from IFS in Cappellari 2016).

The first generation of IFS surveys included the following projects: SAURON (Spectroscopic Areal Unit for Research on Optical Nebulae), ATLAS$^{\mathrm{3D}}$ and CALIFA (Calar Alto Legacy Integral Field Area Survey). They are all completed and the main results important for the present paper are as follows.

SAURON: Emsellem et al. (2004) studied 48 ETGs and estimated velocity, velocity dispersion and the Gauss-Hermite parameters h_3 and h_4 out to $\sim 1\ R_e$. Cappellari et al. (2006) used 2I Jeans and three-integral Schwarzschild dynamical models for a sample of 25 ETGs inside $\sim 1\ R_e$ and discovered that DM contributes to ~ 30 per cent of the total dynamical mass.

ATLAS$^{\mathrm{3D}}$: Cappellari et al. (2013) analyzed the problem of the mass-to-light ratio and DM in their sample, calculated total mass-to-light ratios within $\sim 1\ R_e$ and found median value of DM fraction, $f_{\mathrm{DM}} = 13$ per cent.

CALIFA: Approximately 200 galaxies (out of approximately 600 objects) from the CALIFA sample of nearby galaxies belong to the ETG class (Sánchez et al. 2012).

The stellar kinematic maps, which include velocities and velocity dispersions, of approximately 300 galaxies are presented in Falcón-Barroso et al. (2017).

The second generation of IFS which is still producing results includes the following surveys: MUSE (Multi Unit Spectroscopic Explorer), MASSIVE, SAMI (The Sydney AAO Multi Integral Feld) and MaNGA (Mapping Nearby Galaxies at APO).

MUSE: Several ETGs were explored with MUSE. For example, the low-luminosity S0 galaxy NGC 5102 (Mitzkus, Cappellari & Walcher 2017) was analyzed interior to $\sim 1\ R_e$ and a DM fraction of 0.37 ± 0.04 inside 1 R_e was found.

MASSIVE: In Veale et al. (2017) spatially resolved stellar angular momentum, velocity dispersion, and higher moments of the 41 most massive local ETGs were analyzed and it was found that the luminosity-weighted average h_4–parameter, $< h_4 >_e$ is positive, for all 41 ETGs in their sample which is in agreement with the study of Vudragović, Samurović & Jovanović (2016) who found that in the innermost parts of ETGs radial anisotropies with $h_4 > 0$ dominate.

SAMI: In van de Sande et al. (2017) the stellar kinematics on a sample of 315 galaxies, without a morphological selection was measured between 1 and 2 R_e.

MaNGA: The MaNGA survey is part of the SDSS-IV and provides spectral measurements of approximately 10000 nearby galaxies. Rong et al. (2018) used the Jeans dynamical modeling to find that there exists a 1σ significant difference between the acceleration relations of the fast and slow rotators from the MaNGA database.

4. OTHER TRACERS OF GRAVITATIONAL POTENTIAL

For study of DM in ETGs beyond several effective radii ($2 - 3\ R_e$) other methods and approaches are needed. The X-ray approach which does not suffer from the mass-anisotropy degeneracy can be used for this purpose (see e.g., Samurović 2007 and references therein for possible problems). Another possible approach includes the study of stellar shells for the purpose of estimating gravitational fields of ETGs at large galactocentric radii (see e.g., Bílek et al. 2016). Also, tracers such as PNe and GCs in ETGs can be used for establishing the total mass of a given galaxy. Again, it is necessary to solve the Jeans equation (Eq. 4). In Samurović 2019 one can find the description of the necessary steps in such a procedure and more examples of the use of PNe and GCs in the study of DM in ETGs.

4. 1. PLANETARY NEBULAE

PNe are detectable even in moderately distant galaxies through their strong emission lines and proved to be a useful tool in a search for DM in ETGs.

One of the most studied ETGs using the Jeans equation based on both PNe and GCs is the giant elliptical NGC 5128 (Centaurus A). Hui (1993) identified over 400 PNe and applied the spherical Jeans equation to model the observed velocity dispersion profile out to 25 kpc and detected the existence of DM. Hui, Freeman & Dopita (1995) again relied on PNe as tracers and found that the mass-to-light ratio in its central region approximately equal to 3.9 rises to approximately 10 at 5 R_e (in the B-band) which confirmed the existence of the dark halo. Peng, Ford & Freeman (2004) detected 780 spectroscopically confirmed PNe in NGC 5128 and found that DM is necessary to explain the observed stellar kinematics. Samurović (2010) used PNe in NGC 5128 and found that the isotropic Newtonian mass-follows-light models without DM may provide successful fits out to $\sim 6.4\ R_e$ and that to obtain a good fit in the outermost region ($\sim 10.7\ R_e$) either DM or the existence of tangential anisotropies is needed. The existence of DM in the elliptical galaxy NGC 3379 was studied using PNe in Ciardullo, Jacoby & Dejonghe (1993) who measured radial velocities of 29 PNe (out to $3.8\ R_e$) and found that there is no need for DM. Ten years later, this galaxy was a subject of the study of Romanowsky et al. (2003) who observed PNe in 3 galaxies (NGC 821, NGC 3379 and NGC 4494) and relying on the spherical Jeans models confirmed the lack of DM in NGC 3379 using much larger sample of 109 PNe (out to $\sim 3.5\ R_e$). Samurović & Danziger (2005) analyzed the interior region of NGC 3379 (inside $\sim 1\ R_e$) with long-slit spectra using the Jeans equation and found that DM is not needed there. Douglas et al. (2007) detected 191 PNe of NGC 3379 and using Jeans dynamical models found that inside $5\ R_e$ the mass-to-light ratio in the B-band is $8 < M/L_B < 12$ and that the DM fraction inside this radius is below 40 per cent.

4. 2. GLOBULAR CLUSTERS

One of the earliest examples of usage of GCs in ETGs is the work of Mould et al. (1990) who obtained optical multislit spectra of two giant ellipticals, M49 and M87, from the Virgo cluster and inferred the existence of DM there because of the flat velocity dispersion profiles. Another interesting example of the massive elliptical from the Fornax cluster is NGC 1399. Grillmair et al. (1994) studied the radial velocities of 47 GCs in NGC 1399 and assuming isotropic distribution of the GCs obtained a lower limit on a globally constant mass-to-light ratio of $M/L_B = 79$ which implied strong presence of DM in the outer part of the galaxy. In Samurović & Danziger (2006) it was shown that although the velocity dispersion of NGC 1399 decreases between 4 and $10\ R_e$ there is evidence of DM beyond $\sim 3\ R_e$. This galaxy was re-analyzed using 790 GCs as tracers of the gravitational potential in Samurović (2016) and using the Jeans equation it was shown that a significant amount of DM is needed.

The significant contribution to the study of DM in ETGs has come from the SLUGGS (SAGES Legacy Unifying Galaxies and GlobularS) survey: Pota et al. (2013) analyzed kinematics for over 2500 GCs of 12 ETGs. The SLUGGS sample was used in Samurović (2014): 10 ETGs were studied and in Newtonian approach only one ETG, NGC 2768, could be modeled without DM; three galaxies (NGC 1400, NGC 3377 & 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 their outer parts and NGC 4486 is the only galaxy that needs significant amount of DM even in its inner region. The remaining 5 galaxies require a significant amount of DM beyond $\sim 2 - 3\ R_e$, and the largest mass-to-light ratio was found in NGC 5846 for which $64.2 < M/L_B < 127.4$ beyond $\sim 6\ R_e$ was established.

Bílek, Samurović & Renaud (2019) studied using the Jeans equation 17 ETGs based on their GCs. For the total sample the median contributions of DM inside $1\ R_e$ and $5\ R_e$ are 20 and 72 per cent, respectively. The DM fractions of the slow rotators are much higher than that of the fast rotators: for the fast rotators the DM fractions are equal to 18 and 69 per cent inside 1 and $5\ R_e$, respectively, whereas for the slow rotators the DM fractions become 40 and 88 per cent at the same radii, respectively.

Samurović & Vudragović (2019) analyzed two massive nearby ETGs, NGC 4473 and NGC 4697, both fast rotators using the data from the SLUGGS database. To calculate the contribution of the visible, stellar, component the 1.40 m "Milanković" telescope mounted at Vidojevica was used to obtain the deep photometry in the B- and V-bands. NGC 4473 was modeled interior to $\sim 12\ R_e$ and NGC 4697 was modeled interior to $\sim 3\ R_e$ using 3 cases of anisotropies. Newtonian purely baryonic models for both galaxies in most cases could not provide a successful fit of the observed velocity dispersion without the additional, dark component. However, the solutions for both galaxies based on purely baryonic tangentially anisotropic models were found.

5. CONCLUSIONS

The year 2019 marked the centenary of the publication of the James Jeans' book *Problems of Cosmogony and Stellar Dynamics* in which he presented the equations that are now known and used as the Jeans equations.

It was shown that the Jeans equations remain an indispensable tool in the study of galaxies, especially massive ETGs and the problem of DM in them. The application of the usage of the Jeans equations in massive nearby ETGs in case of integrated stellar spectra in galaxies (both long-slit and integrated field spectra), and other tracers of gravitational potential (PNe and GCs) was discussed.

Some future work related to DM in ETGs will include: the study of trends in population and kinematics at radii beyond $\sim 2\ R_e$, studies of the problem of stellar population and the analysis of initial mass functions in ETGs, studies of the trends in total density profiles at large galactocentric distances where DM is expected to dominate and the comparison with spirals.

The new "Milanković" 1.40 m telescope mounted at the Astronomical Station Vidojevica run by the Astronomical Observatory of Belgrade has proven to be a very useful tool in obtaining images of nearby ETGs thus providing the information on the stellar content inside several effective radii.

Acknowledgements

This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (MESTDRS) through the contract No. 451-03-68/2020-14/200002. Useful discussions with Dr. M. Bílek, Dr. A. Vudragović, M. Jovanović, Dr. O. Vince, Dr. M. Ćirković, Dr. B. Vukotić and Dr. S. Knežević are acknowledged, as well as the work of the technical operators at the Astronomical Station Vidojevica, M. Sekulić and P. Kostić. The financial support by the European Commission through project BELISSIMA (BELgrade Initiative for Space Science, Instrumentation and Modelling in Astrophysics, call FP7-REGPOT-2010-5, contract No. 256772) which was used to procure the 'Milanković' 1.40 m telescope with the support from the MESTDRS is acknowledged as well as the the continued support of the MESTDRS related to the work of the Astronomical Station Vidojevica. The author thanks the referee for useful comments.

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