PhD name: Caterina Caravita
PhD Cycle: XXXIV
Tutors: Luca Ciotti, Silvia Pellegrini

RESEARCH PROJECT: Dynamical modelling of stellar populations and dark matter in galaxies

Scientific rationale

Galaxies are complex systems, composed of different matter components, such as stars, interstellar medium, an extended dark matter (DM) halo, a central supermassive black hole (BH). The stellar dynamics plays an important role in connecting many aspects of galaxies, and stellar systems in general, such as also open and globular clusters. From one side, the stellar orbits are of course determined by the structure, and the history, of the system, including the amount and distribution of the other matter components. On the other side, in turn, the stellar dynamics influences the evolution of the whole galaxy, for instance, galactic rotation can affect cooling flows, leading to the formation of cold gas disc and consequent star formation, and stellar disc instabilities, leading for example to the formation of a bar. The development of rigorous modelling techniques for the internal structure and dynamics is crucial for the understanding of physical processes in real galaxies. Beyond a pure theoretical interest, in the era of integral field spectroscopy (IFS) and large surveys, and of high-perfomance computing, more and more sophisticated galaxy models are required for the interpretation of observed galaxies and for simulations of their evolution.

Project aims

My work is based on the development of a theoretical approach, implemented in a flexible numerical code, for the dynamical modelling of axisymmetric galaxies with multiple stellar components. Analytical models of single and multicomponent axisymmetric galaxies are available only in few cases; moreover, while of fundamental importance in elucidating physical concepts behind the stellar dynamics, and so in guiding the construction of more realistic galaxy models to be carried out numerically, analyitcal models necessarily suffer from the restrictions imposed by the request of analytical tractability, and they miss the flexibility of a numerical treatment. Analytical and numerical modelling should be seen as complementary approaches, and indeed I often exploit analytical methods in my work. In my studies, I am also using these models to provide appropriate initial conditions for hydrodynamical simulations of gas flows and AGN feedback in early-type galaxies (ETGs), and for N-body simulations of the stability of disc galaxies. Finally, the stellar properties obtained by our modelling are also comparable with the observed morphological and kinematical fields of galaxies, as provided by observations from IFS.

Methods & results

Modelling procedure & JASMINE2 code Our numerical modelling is based on the solution of the Jeans equations for axisymmetric stellar systems, in cylindrical coordinates, and is especially designed to build (and project) multicomponent systems, in a fast and flexible way. We developed the theoretical framework, and I implemented it in the numerical code JASMINE2 (**Caravita et al. 2021, MNRAS, 506, 1480**). The galaxy models are composed of an arbitrary number of matter components: different stellar components, DM components, and a central supermassive BH. Each stellar density component is characterised by different structural (density profile, flattening, total mass, scale length), dynamical (rotational support, velocity dispersion anisotropy), and stellar population (age, metallicity, initial mass function, mass-to light ratio) properties. In particular, it is assumed to be described by a two-integral (also extended to three-integral) distribution function, requiring a kinematical decomposition for the azimuthal velocity field. I introduced a new *generalised* k-decomposition, suitable when the most commonly used Satoh k-decomposition cannot be applied: for example, it necessarily occurs in modelling a multicomponent stellar system with spherically symmetric total stellar density, or in case of prolate ellipsoidal stellar distribution.

In order to efficiently explore the parameter space (that can be very large for multicomponent models), I exploit all the *scalings* allowed by the Poisson and the Jeans equations. The modelling procedure is organised in two distinct parts, and so it is implemented in JASMINE2: the *Potential & Jeans Solver* and the *Post-Processing* phase (PP). The Potential & Jeans Solver computes the *scaled* (normalised and dimensionless) potentials and then solves the Jeans equations for each scaled stellar density component in each scaled potential component. In the second PP phase, the scaling parameters are fixed, i.e the mass and luminosity weights, and the kinematical decompositions; the scaled solutions of the Jeans equations are combined, and the resulting structural and kinematical fields are projected along a given line-of-sight. This procedure allows to drastically reduce the computational time needed for the construction of a multicomponent galaxy model, also gaining in flexibility in the variation of the model parameters: with a single run of the Potential & Jeans Solver, one can build a *family* of galaxy models, characterised by the same set of scaled solutions; then each specific model is defined by fixing suitable values for the scaling parameters in the PP phase.

The theoretical approach, and its numerical implementation, have been deeply tested against analytical solutions available in literature, in particular in case of homoeoidal expansion. As first direct applications, I built few illustrative galaxy models, showing some interesting properties of multicomponent stellar models, such as, for instance, complex morphologies, counter-rotation of the kinematical components, spatially-varying anisotropy, gradients of mass-to-light ratio. Moreover, I reproduced the decomposition of a double-exponential disc with three Miyamoto-Nagai (MN) discs, by extending previous works in literature to the study of the Jeans equations and of the projected fields. In particular, the line-of-sight velocity dispersion shows remarkably different behaviours of the models, suggesting some care in using simpler MN discs instead of exponential discs.

Computation of the gravitational potentials In the code JASMINE2, for the computation of the potentials of the stellar and DM distributions, I exploit full analytical solutions when known, or numerical evaluations. For any density distribution, the potential can be computed in terms of complete elliptic integrals of the first kind, a very accurate but also time-expensive method. In order to reduce the computational time required for the potential evaluation (the most time-consuming part of the numerical procedure), I implemented the Chandrasekhar formula for ellipsoidal density distributions, and an integral formula based on Bessel functions for discs. In particular, for factorised discs for which one can calculate analytically some radial and vertical expressions, the formula reduces to a one-dimensional integration in terms of Bessel functions of the first kind: we developed a quite general method (**Caravita & Ciotti in preparation**) which can be applied to a variety of radial and vertical distributions, allowing for a fast computation of the potential, for instance, of exponential discs, with infinitely thinness or vertically decreasing with an exponential law (double-exponential discs), or with the sech^n (pseudo-isothermal exponential discs). Finally, I also implemented the homoeoidal-expanded formulae for a number of ellipsoidal density-potential pairs, which are fully analytical in the limit of small flattenings of the density distributions.

The possibility of a flexibile exploration of the parameter space of multicomponent galaxy models makes our modelling procedure a useful complementary tool for numerical simulations of galaxy evolution. I am involved in two main works on this field.

Evolution of ETGs with hydrodinamical simulations Through hydrodynamical simulations performed with the code MACER (developed by Ciotti, Ostriker and collaborators), we investigated the dependence of some global properties of massive ETGs on their internal structure and dynamics, modeled with our code JASMINE2 (**Ciotti, Ostriker, Gan, Jiang, Pellegrini, Caravita, Mancino 2021 in submission**). In particular, we studied the effects of BH accretion and AGN feedback on cooling flows in rotating axisymmetric ETGs, considering the formation of HI discs on the equatorial plane of the galaxy, and the star formation, taking into account also disc instabilites and gas viscosity; the temperature and luminosity of the X-ray emitting gas of the hot corona; the total gas mass ejected from the galaxy, with the addition of the confining effect of a group/cluster DM halo. These properties have been analysed for a set of galaxy models, varying their total mass and rotational support, and finding results in good agreement with real observed ETGs.

Stability of disc galaxies with N-body simulations During my Marco Polo project, I started the study of the evolution of stellar discs, through N-body simulations performed with the code GADGET2, and the relation between the initial model parameters and the successive development of instabilities, in particular with respect to bar formation, with the aid of our code JASMINE2 (**Caravita, D'Onghia, Ciotti, Pellegrini in preparation**). I highlight some limits of the well-known Ostriker-Peebles global (i.e. non local) stability parameter, which may predict in a quite satisfactory way the development of disc instabilities in certain cases, but at the cost of failing in some other relevant physical situations. I look for a global stability parameter, which is a good diagnostic for future instabilities, and takes rigorously into account the physical causes, such as for example the amount of DM surrounding the disc or of an inner mass distribution (e.g. BH, stellar bulge), in addition to the kinematic of the disc itself.

WORKSHOPS, CONFERENCES & MEETINGS

I) 27-31 May 2019, Bologna – Star Clusters: from the Milky Way to the Early Universe
(IAU Symposium 351 & MODEST 19)
LOC & poster: *Dynamical models of spheroidal multi-component stellar systems*

I) 3 July 2019, Bologna – MidWeek Talk of PhD students
Talk: *Dynamical models of Early-Type Galaxies*

I) 28-31 October 2019, Trieste - Galaxy Evolution and Environment (GEE6)
Poster: *Dynamical models of Early-Type Galaxies with multiple stellar populations*

II) 18-22 November 2019, Milano – The Art of measuring galaxy Physical Properties (APP)
Poster: *Dynamical models of Early-Type Galaxies with multiple stellar populations*

III) 3-4 December 2020, online (Sidney) – Linking the Galactic and Extragalactic

III) 20 January 2021, online (Bologna) – Weekly Phd Seminars (WPS)
Talk: *Mulicomponent dynamical modelling of axisymmetric galaxies*

III) 29 January-12 February 2021, online (Bologna) – Series of seminars: How to write a scientific paper; How to give a scientific presentation; What is a model? An evolution perspective.

III) 10-12 February 2021, online (ZAH, Heidelberg) – MW-GAIA Workshop 2021

III) 12-16 April 2021, online (ESO) – Extagalactic Spectroscopic Surveys. Past, present and future of galaxy evolution (GALSPEC 2021)

III) 13 December 2021, University of Wisconsin-Madison
Talk: *Mulicomponent dynamical modelling of axisymmetric galaxies & investigation of the disc stability with N-body simulations*

PhD SCHOOLS

I) 25-27 February 2019, IRA Bologna - ALMA Science and Proposals Workshop

II) 14-16 October 2019, INAF-OAS Bologna – Tinkering, coding e gaming per la didattica dell'astrofisica

III) 14-18 September 2021, online (Bologna) – Officina di Narrazione della Scienza (ONSCI)

INTERNAL COURSES

I) 17-25 June 2019, Bologna - Statistics for Astrophysics

II) 27 May-22 July 2020, online - Neutrinos and Dark Matter in Astro- and Particle Physics

II) 17-22 September 2020, online (Bologna) – GAIA: Great Advances In Astrophysics

III) 30 November-2 December 2020, online (Bologna) – The Interstellar Medium

III) 19-23 April 2021, online (Bologna) - Gamma Ray Bursts: from observations to physical properties

III) 5-14 May 2021, online (Bologna) – Writing, talking & presenting Science

ISA LECTURES

I) 8 October 2019 - *Power Tools for New Plants to Feed 10 Billion People by 2050*

I) 15 October 2019 - *New Wealth, Old Poverty: The Urgent Need for New Institutional Arrangements*

II) 12 November 2019 – *This turbulent turbulent world*

II) 19 May 2020 - *Exploration of small bodies of the Solar System: focus on comets*

III) 19 October 2021 - *Covid-19 and Dante's Hell: Venturing from a Black Hole on the Thread of a Tune*

III) 16 December 2021 – *Knowing the Earth in the Digital Era*

OTHER RELEVANT ACTIVITIES

I) Local Organising Commitee (LOC) for Star Clusters: from the Milky Way to the Early Universe (IAU Symposium 351 & MODEST 19) - 27-31 May 2019, Bologna

II-III) Representative of the PhD students in the "Collegio di Dottorato"

III) Co-supervisor of the Master Thesis of Luigi Zallio. Supervisor: Luca Ciotti.

PRIN 2019: *Astrophysics in STEM: learning through tinkering, coding and gamification.*
PI: Sara Ricciardi
Accepted

PRIN 2020: *Early Formation and Evolution of Bulge and HalO (EFEBHO)*
PI: Giuseppe Bono
Submitted

RESEARCH PERIOD ABROAD

November-December 2021 (postponed and restricted to one month due to the pandemic) - **Marco Polo**
University of Wisconsin-Madison (USA) – Astronomy Department
Collaboration with Prof. Elena D'Onghia
Project title: *Stability of disc galaxies through dynamical models and N-body simulations*

PUBLICATIONS

FIRST AUTHOR

Dynamical models of spheroidal multi-component stellar systems
Caravita C., Ciotti L., Pellegrini S., 2020, IAUS, 351, 273

Jeans modelling of axisymmetric galaxies with multiple stellar populations
Caravita C., Ciotti L., Pellegrini S., 2021, MNRAS, 506, 1480

An efficient method to compute the gravitational potential of disc galaxies
Caravita C., Ciotti L., In preparation

Stability of disc galaxies through dynamical models and N-body simulations
Caravita C., D'Onghia E., Ciotti L., Pellegrini S., In preparation

CO-AUTHOR

A parameter space exploration of high resolution numerically evolved ETGs including AGN feedback and accurate dynamical treatment of stellar orbits
Ciotti L., Ostriker J. P., Gan Z., Jiang B. X., Pellegrini S., Caravita C., Mancino A., 2021 in submission