Dynamical Masses of Local Group Galaxies
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Dynamical modelling of galaxies with DYNAMITE

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Abstract. The combination of kinematic and chemical information from Galactic stars has revealed in great detail the structure, dynamics and history of our own Galaxy. In external galaxies, it is impossible to map the distribution of individual stars, but high signal-to-noise integral field unit (IFU) spectroscopy data at various wavelengths, together with sophisticated dynamical models, give us the opportunity to gather information on the structure, dynamics and formation history of these systems. The Schwarzschild method models galaxies through the superposition of stellar orbits, and is equipped to deal with very detailed kinematic measurements, allowing us to take full advantage of high-quality IFU datasets of nearby galaxies. Here we present an implementation of this method called DYNAMITE. We provide an overview of the modelling technique, introduce applications to observations and simulations, and anticipate our future plans for DYNAMITE.

Keywords. Galaxies: kinematics and dynamics, Galaxies: structure

1. Introduction

Dynamical modelling is a key instrument for studying the evolution of galaxies, because it allows us to investigate properties of these systems that are not directly observable, such as those relating to dark matter and black holes. In particular, measuring the total mass of galaxies and determining the relative contribution of luminous and dark matter is important for studying galactic evolution, and has implications for our understanding of structure formation and evolution in a cosmological context. Different approaches can be used to describe the dynamics of galaxies (e.g., see Rix & Bovy 2013), going from spherical and axisymmetric models defined by an analytical distribution function (e.g., Nagai & Miyamoto 1976; Qian et al. 1995; Magorrian et al. 1998) to Jeans modelling (e.g., Cappellari 2008), and to made-to-measure models (e.g., Syer & Tremaine 1996; Bovy, Kawata, & Hunt 2018).

Another popular approach, and the focus of this contribution, is the orbit-superposition method first developed by Schwarzschild (1979). With this technique, starting from an assumed galactic potential (that accounts for both the visible and dark matter), an orbit library is calculated, and for each orbit the relevant observables are recorded. Through a fit to the observed surface brightness and kinematic data, the particular superposition of orbits that best represents the data is constructed. This procedure makes it possible to use constraints coming from very detailed kinematic measurements, enabling a study of the intrinsic dynamical structure of galaxies in great depth. Several implementations of the triaxial Schwarzschild method exist, such as those proposed by van den Bosch et al. (2008), Vasiliev & Valluri (2020) and Neureiter et al. (2021). This modelling approach has been successfully applied to multiple galaxies, to study their internal structure (e.g., Cappellari et al. 2007; Feldmeier-Krause et al. 2017; Jin et al. 2020; Santucci et al. 2022;

Pilawa et al. 2022), to determine their dark matter content (e.g., Thomas et al. 2007; Cappellari et al. 2013; Poci, Cappellari, & McDermid 2017; Santucci et al. 2022), to measure the mass of their central super-massive black holes (e.g., van der Marel et al. 1998; Valluri, Merritt, & Emsellem 2004; Thater et al. 2019; den Brok et al. 2021; Thater et al. 2022; Merrell et al. 2022), and to identify accreted components (e.g., Zhu et al. 2020, 2022; Poci et al. 2021).

In the following we will focus on the publicly released software DYNAMITE (Jethwa et al. 2020; Thater et al. 2022), which is based on the code introduced by van den Bosch et al. (2008). We will describe the structure of the code, illustrate some of the applications for which this has been used, and outline the future enhancements that are currently planned for it.

2. The DYNAMITE code

DYNAMITE† (DYNamics, Age and Metallicity Indicators Tracing Evolution, Jethwa et al. 2020; Thater et al. 2022) is a triaxial dynamical modelling code, mainly aimed at studying the assembly history of galaxies by combining dynamical information (obtained from orbital distribution) with age and metallicity from population synthesis models. It is based on the orbit-superposition method proposed by Schwarzschild (1979).

DYNAMITE is the publically released successor of the triaxial Schwarzschild code developed by van den Bosch et al. (2008), and it is an open-source Python package, with a well-documented application programming interface. With respect to its predecessor, the DYNAMITE code has new features, such as for example the possibility to fit orbit-based models to histogrammed line-of-sight velocity distributions (LOSVDs) extracted by means of the BayesLOSVD framework (Falcón-Barroso & Martig 2021), instead of using Gauss-Hermite LOSVDs. The additions to the code and the developments planned for the future are all driven by relevant scientific questions, as illustrated in Section 3.

Figure 1 shows a scheme of the main steps needed to run DYNAMITE, which will be briefly illustrated in the following. This scheme is also a useful representation of the structure and components of the code.

Before running DYNAMITE, it is necessary to prepare the data in the correct format, i.e., to "translate" the observed kinematic data into files that are directly readable and usable by DYNAMITE. At this stage, the user can decide whether to use Gauss-Hermite moments or BayesLOSVD to characterize the kinematics; in both cases, to prepare data for use in DYNAMITE, an `astropy ecsv` file has to be created, together with some auxiliary files. At the moment, DYNAMITE accepts as input kinematic data obtained with integrated light spectroscopy, but future additions will also include the possibility to fit discrete line-of-sight velocity data and proper motions. The surface mass density and surface brightness are represented by Multi Gaussian Expansions (MGEs), also written in `astropy ecsv` format. If the assumption of a constant mass-to-light profile is valid for the stellar system under consideration, the two sets of MGEs can be identical, otherwise two different sets of MGEs need to be used, to represent light and mass respectively.

A configuration file in the `yaml` format needs to be specified in order to run DYNAMITE. This file contains two sections, where the user defines some properties of the physical system under consideration, and some settings for the modelling procedure. For example, in the first part, the user sets the starting values, step size and limiting values to be used for the parameter exploration, and can fix some parameters to specific values, if they are not fitting parameters. DYNAMITE models can contain

† The code is available on github (`https://github.com/dynamics-of-stellar-systems/dynamite`), and the documentation is also available online (`https://dynamics.univie.ac.at/dynamite_docs`).

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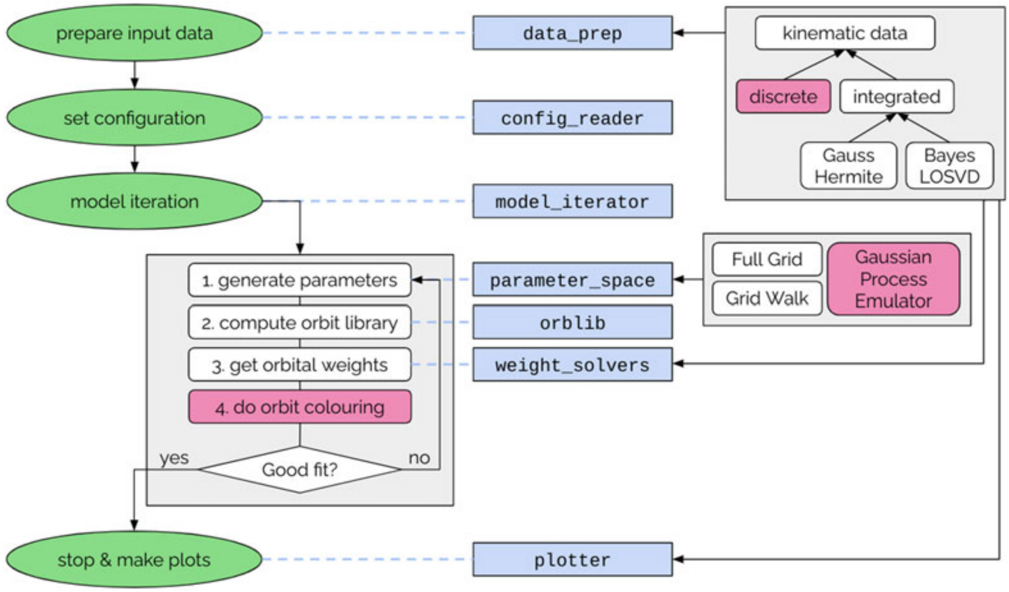

Figure 1. Scheme illustrating the basic steps of a DYNAMITE run, listed on the left in the oval green boxes. The pink boxes represent tasks that will be implemented in DYNAMITE in the future. Blue boxes indicate the relevant parts of DYNAMITE responsible for the tasks to which they are connected with blue dashed lines.

three different components: the stellar component, described by means of the parameters q, p, and u, representing the axis ratios and therefore describing the morphology of the system; a dark matter halo following a spherical Navarro-Frenk-White profile (NFW, Navarro, Frenk, & White 1996), defined by means of the concentration c and dark matter fraction f; and a central black hole, for which the mass m can be specified. In the second part of the configuration file, the user sets the dimensions of the orbit library to use, the type of weight solver and parameter generator, and multiprocessing settings.

After providing the input data and configuration file, it is possible to start a model iteration. For each choice of parameters, generated with the method specified in the configuration file, an orbit library is computed, and the corresponding orbital weights are determined, so that the superposition of orbits closely represents the data (as described in Schwarzschild 1979). This process is repeated to minimize the corresponding χ^2 function, and it is stopped when the relevant criteria set in the configuration file are met.

The best-fit model can then be used to make some plots, both to show how well the model reproduces the data and to inspect some properties of the model. As an example, Fig. 2 shows the comparison between the observed photometric and kinematic maps of galaxy NGC 4191 (panels in the left column) and the maps representing the best-fit model obtained with DYNAMITE (middle column); residuals are also shown in the right column.

3. Applications of DYNAMITE

Both DYNAMITE and the original code developed by van den Bosch et al. (2008) have been used to model the dynamics of many galaxies in the past years. A summary of the large galaxy samples that have been modelled with this code is presented in Table 1. The variety of galaxies modelled with this method and the application to data from different observing surveys reflects the plethora of scientific questions that this modelling

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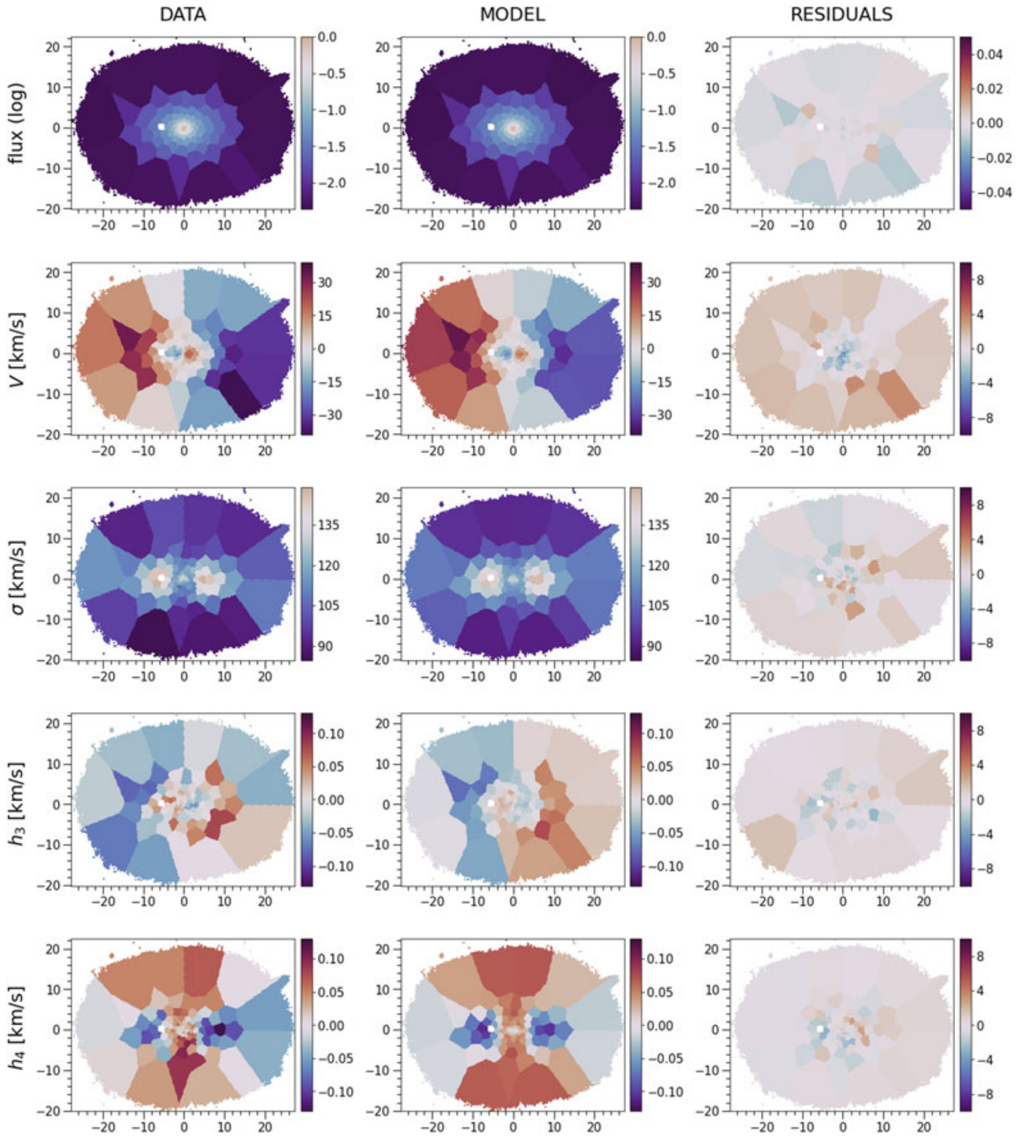

Figure 2. Comparison between the data obtained for galaxy NGC 4191 and the best-fit DYNAMITE model (Rubino et al. in prep.). The left column shows the observed photometric and kinematic maps, the middle column the ones corresponding to the best-fit DYNAMITE model, and the right column the residuals. From top to bottom, the maps represent surface brightness, mean velocity, velocity dispersion, and h_3 and h_4 Gauss-Hermite moments, indicating skewness and kurtosis deviations from a Gaussian velocity distribution.

approach can address. Some examples of what can be done with DYNAMITE, and of the upcoming further improvements to the code are presented in the following.

Thanks to the use of the BayesLOSVD framework to fit models to histogrammed LOSVDs, it is possible to describe galaxies with counter-rotating components in order to investigate their formation mechanisms. Two examples are the S0 galaxies NGC 4191 and IC 719, which are known to host two large-scale counter-rotating stellar disks (Coccato et al. 2015; Pizzella et al. 2018). The best-fit model obtained with DYNAMITE for NGC 4191 (Rubino et al. in prep.) is shown in Fig. 2, and provides a good representation of the kinematics of this galaxy.

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Table 1. Overview of DYNAMITE galaxy models. For each observational survey listed in the first column, the type (second column) and number N (third column) of galaxies modelled with DYNAMITE are indicated; the corresponding references are listed in the fourth column.

Survey	Galaxy type	N	Reference
CALIFA	early-type and late-type galaxies	300	Zhu et al. (2018)
ATLAS^{3D}	early-type galaxies	$63^{(a)}$	Thater et al. (in prep)
MANGA	early-type galaxies	149	Jin et al. (2020)
SAMI	early-type galaxies	161	Santucci et al. (2022)
Fornax3D	early-type and late-type galaxies	18	Ding et al. (2023)
		(total = 691)	

Notes: $^{(a)}$ The total sample consists of 260 galaxies, whose analysis is in progress.

Efficient options for parameter search allow for a good determination of both the shapes of galaxies, and the properties of super-massive black holes (SMBHs) in relation to their host galactic nuclei. Recently, Santucci et al. (2022) applied DYNAMITE modelling to a large sample of galaxies whose data were collected in the SAMI Galaxy Survey, to recover their morphologies and inner orbit distributions. They found that the majority of galaxies in their sample are oblate, and only a small fraction appear to be prolate. Their results agree with a formation scenario proposing two main channels for the formation of slow and fast rotators, respectively characterized mainly by minor and major mergers, and show that such an investigation can provide clues on the past history of these systems. Dynamical modelling with DYNAMITE of galaxies observed within the ATLAS^{3D} survey is also in progress (Thater et al., in prep.), with the main aim of determining their intrinsic shapes. The Schwarzschild modelling approach is also useful to investigate the properties of SMBHs in the centres of galaxies, and their connection to the properties of their host nuclear star clusters. An example of this is shown in Thater et al. (2023), where DYNAMITE models are used to investigate the dynamics of FCC 47. Using this approach makes it possible to unveil the build-up of galactic centres, exploiting the fact that the evolutionary history of nuclear star clusters is imprinted into their stellar population and kinematics.

Tahmasebzadeh et al. (2022) has recently proposed an implementation of the Schwarzschild orbit-superposition method that allows the inclusion of a bar. This is currently being integrated into DYNAMITE, making it possible to fit in detail the photometry and stellar kinematics of nearby barred galaxies. Aside from a detailed insight into the orbits that built the bar, this will also yield robust measurements of the bar pattern speed, corotation radius and intrinsic bar length, which combined can answer the long-standing question whether bars are slowed down by dark matter haloes.

By inspecting the orbital distribution in a model, it is possible to identify distinct components: cold, warm and hot orbits show properties resembling thin disks, thick disks and classical bulges, respectively, as defined from cosmological simulations (Zhu et al. 2018, 2020). A colouring can be added to orbits, to reproduce metallicity and age maps on top of kinematic maps. This crucial upcoming addition to the DYNAMITE code will enable us to uncover the assembly history of galaxies, including past mergers (Zhu et al. 2022).

4. Conclusion

DYNAMITE is a user-friendly and flexible tool to construct detailed dynamical models of nearby galaxies. Based on Schwarzschild's orbit-superposition approach, it makes it possible to study morphological and dynamical properties of galaxies in detail, and to disentangle their complex build-up. DYNAMITE and its predecessor have been applied to

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about 700 (early-type and late-type) observed galaxies, and to several simulated galaxies, always providing a good representation of the data. The foreseen additions to the code, namely the inclusion of a barred structure and of orbit colouring, will expand the reach of this modelling tool, and will enable the users to answer many more pressing scientific questions, especially now that new and more detailed data are unveiling the complexity of galaxies and of their past evolutionary histories.

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