Self-consistent dynamical models for early-type galaxies in the CALIFA Survey

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ABSTRACT

We present the first application of self-consistent, continuous models with distribution functions (DFs) depending on the action integrals, to a sample of nearby early-type galaxies in the CALIFA Survey. Each model is axisymmetric, flattened, anisotropic and rotating and the total gravitational potential is self-consistently generated by the density distribution. The spatially-resolved kinematics of the CALIFA Survey gives solid constraints to the models' parameters: we fit the galaxies' surface brightness and the galaxies' spatially resolved kinematics and we estimate dynamical masses in agreement with other dynamical modelling approaches. For each galaxy, the best model provides an analytic DF which fully characterizes the velocity distribution of the stars. The fact that the DF depends on the action integrals makes it easy to extend the present models to have multiple components, such as bulge, stellar disc and dark and stellar halo, in equilibrium with their self-consistent gravitational potential.

Keywords: Galaxy kinematics & dynamics, dark matter, elliptical galaxies

1. SELF-CONSISTENT EQUILIBRIUM MODELS

Equilibrium models are a fundamental tool to study the internal kinematics and dynamics of galaxies, in such they provide a complete characterization of the system's dynamical state and they can be tailored to reproduce virtually any observable quantity that can be measured with modern telescopes. When observations of the kinematics of stars in galaxies along the line-of-sight, obtained via e.g., analysis of the stellar absorption lines in the galaxy's optical spectrum, are used to constrain the galaxy's gravitational potential using dynamical models, one derives robust constraints on e.g., the total mass distribution, the stellar velocity distribution and the stellar angular momentum (see e.g., [1]).

Here we present a new family of self-consistent, axisymmetric, flattened, anisotropic and rotating equilibrium models with analytic distribution functions (hereafter DFs) which depend on the three action integrals $\mathbf{J} = (J_\mathrm{r}, J_\phi, J_\mathrm{z})$. These models are an extension of the spherical and almost isotropic models of Posti et al. (2015, see [2]). The DF $f = f(\mathbf{J})$ is composed of parts even and odd in the angular momentum J_ϕ: the even part, $f_+(\mathbf{J})$, is a double power-law of the three actions, which generates a double power-law density distribution; whereas the part odd in J_ϕ is $f_-(\mathbf{J}) = \tanh(\chi J_\phi/J_0)\, f_+(\mathbf{J})$, where χ is a dimensionless parameter controlling the model's rotation curve and J_0 is a scale action at which the model's density profile has the characteristic break. The observables such as light and velocity distribution are computed by integrating the DF in velocity space, e.g., for the density we solve $\rho(\mathbf{x}) = \int \mathrm{d}\mathbf{v}\, f[\mathbf{J}(\mathbf{x}, \mathbf{v})]$, where the map $(\mathbf{x}, \mathbf{v}) \mapsto \mathbf{J}(\mathbf{x}, \mathbf{v})$ is computed using the Stäckel Fudge algorithm (see [3]). For each model we find the self-consistent gravitational potential Φ using the iterative scheme described in Binney (2014, see [4]).

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Table 1. Sample description and estimated masses and mass-to-light ratios from our $f(\mathbf{J})$ models. (i) galaxy name; (ii) morphological type from isophotal analysis; (iii) semi-major axis of the ellipse containing half of the r-band flux (from SDSS images); (iv) inclination angle derived from the photometry; (v) specific angular momentum within the effective radius (see [7] for a definition); (vi) dynamical mass, within the effective radius, for the best-fitting $f(\mathbf{J})$ model; (vii) r-band mass-to-light ratio.

(i) Galaxy	(ii) Hubble Type	(iii) R_e arcsec	(iv) i	(v) λ_Re	(vi) $M(< R_\mathrm{e})$ $M_\odot$	(vii) M/L $(M/L)_\odot$
NGC 6125	E1	21.8	20	0.1	$1.1 \times 10^{11} M_\odot$	4.4
NGC 2592	E4	9.9	40	0.43	$1.9 \times 10^{10} M_\odot$	5.6
NGC 6427	S0	8.3	75	0.4	$3.1 \times 10^{10} M_\odot$	5.8

2. APPLICATION TO A SAMPLE OF CALIFA EARLY-TYPE GALAXIES

We select a sample of three early-type galaxies with different morphologies and kinematics from the DR2 of the CALIFA Survey (see [5]). The spatially resolved stellar kinematics has been derived using the pPXF algorithm (see [6]) and the details are described in Falcòn-Barroso et al. (in preparation). The main properties of the sample of three early-types are summarized in Table 1.

Our dynamical models are fitted to the first and the second moment of the velocity distribution in each CALIFA spaxel plus to the galaxy's SDSS r-band photometry. We first use the galaxy's r-band photometry to constrain some parameters of $f_+(\mathbf{J})$ (namely, the power-law indexes) and then we use the line-of-sight velocity $v_\parallel$ and velocity dispersion $\sigma_\parallel$ to determine the remaining parameters of f_+ and f_-, related to the model's kinematics. A constant mass-to-light ratio M/L sets simultaneously the normalization of the light distribution and the scale of the system's gravitational potential and also takes into account the possible presence of dark matter in the regions where the fit is computed. A visual representation of the quality of the fit given by our family of $f(\mathbf{J})$ one-component models is given in Figure 1.

3. CONCLUSIONS AND OUTLOOK

We have introduced a new family of axisymmetric, anisotropic and rotating equilibrium dynamical models, whose DF is an analytic function of three action integrals. One advantage of these models, made possible by the fact that the DF is an explicit function of the actions, is that it is possible to use convergent iterative schemes to compute the corresponding self-consistent gravitational potential also in the presence of additional components. We have demonstrated their applicability to the dynamical modeling of external early-type galaxies by fitting the photometry and spatially resolved kinematics of three galaxies in the CALIFA Survey. The quality of the fit that we achieve is comparable to that of other popular dynamical models and we also give an independent estimate of the total mass of these galaxies, which turns out to be in good agreement with estimates with other techniques.

Our models are described by a handful of free parameters and the observable quantities are computed via three-dimensional integrals; therefore, a best-fit $f(\mathbf{J})$ is found in a relatively small amount of time compared to, e.g., orbit-based or particle-based dynamical models. Nevertheless, unlike simple and fast-to-compute models based on the Jeans' equations, an $f(\mathbf{J})$ model completely characterizes the velocity distribution of the stellar system: when considering the amount of physical information that can be extracted and the time necessary to find the best model, our method performs very well compared to other methods.

The free parameters of the DF are responsible for different observable features, therefore the degeneracies in these parameters are minimized. Nevertheless, the model's line-of-sight kinematics is inevitably degenerate with the inclination of the line-of-sight w.r.t. the rotation axis and this is not removed by our method. We break such degeneracy by fixing the inclination angle i derived from the galaxy's photometry via a maximum likelihood

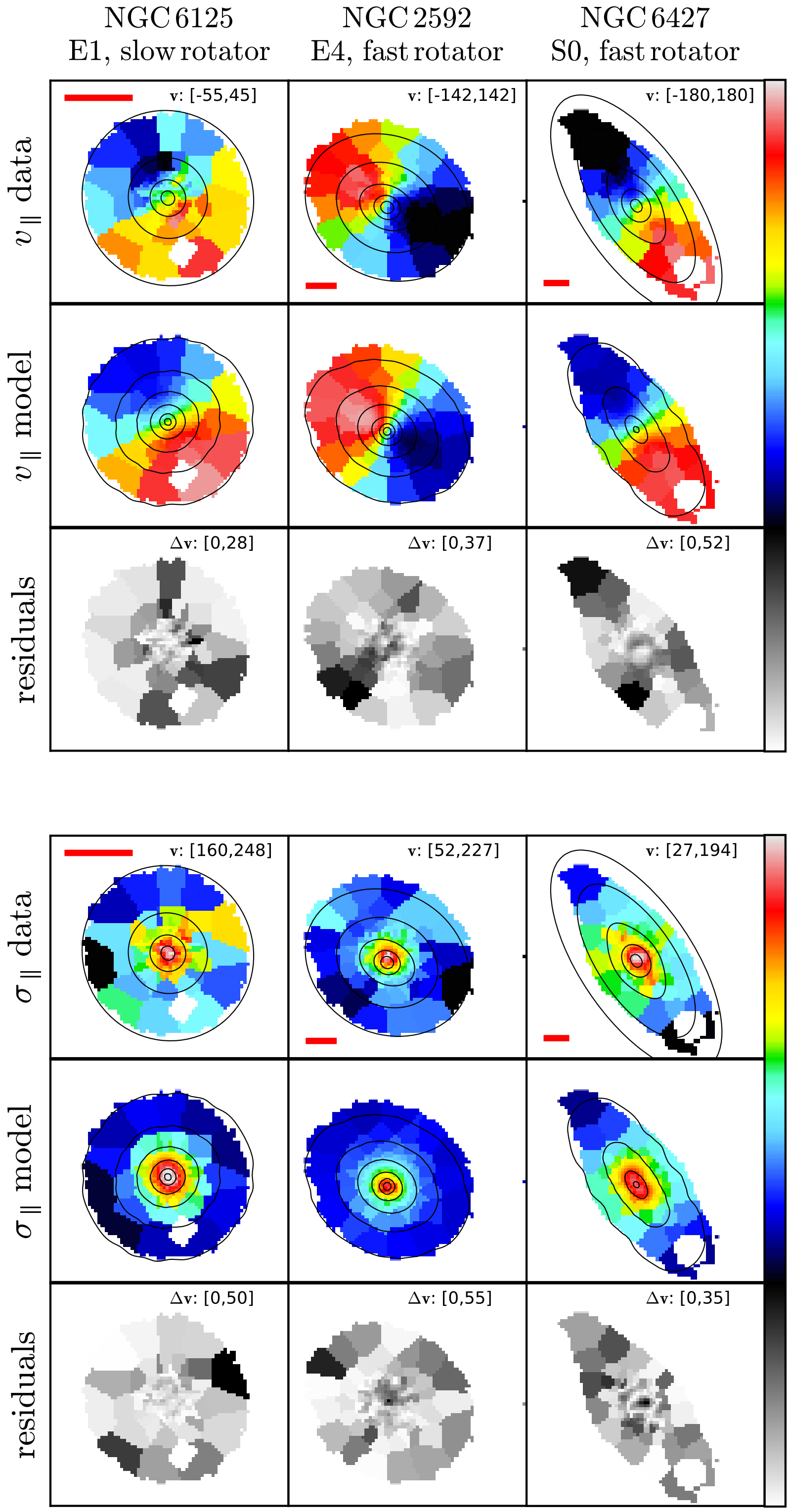

Figure 1. Comparison of NGC 6125's, NGC 2592's and NGC 6427's stellar kinematic maps with the corresponding best $f(\mathbf{J})$ models. The panels are arranged as follows: each column is for a given galaxy listed on top and the two nine-panel blocks refer to the maps of the line-of-sight velocity (top) and velocity dispersion (bottom). In each block, the top row shows the kinematic maps of the galaxies, with overplotted contours of their surface brightness; the central row shows the kinematic maps of the $f(\mathbf{J})$ models, with overplotted isophotal contours; while the bottom row shows the corresponding maps of the residuals. The red bar in the top panel of each block shows the galaxy's effective radius. We use two color scales, one for the residuals maps (grey) and one for the $v_\parallel$ and $\sigma_\parallel$ maps (blue-red), with minimum and maximum values in km/s written for each galaxy.

analysis. This expedient makes the best-fitting model to be a global minimum of the likelihood function (in the region of the parameter space which we explore).

The best $f(\mathbf{J})$ model for the lenticular galaxy NGC 6427 provide a worse fit to the galaxy's photometry than the fits to the other two galaxies. This is most likely because our one-component model tries to fit simultaneously both the bulge and the extended stellar disc of that galaxy, which are of roughly equal importance in determining its photometry. For such a system it is more appropriate to use a two-component bulge-plus-disc model of the type $f(\mathbf{J}) = f_{\rm bulge}(\mathbf{J}) + f_{\rm disc}(\mathbf{J})$. We have already generated models of this latter form which yield a much better fit to the observations and we are currently working on finding the global best-fitting model and on accurately treating the degeneracies on the parameters of the two DFs. Once this is completed, we will have a robust method to perform a kinematical bulge/disc decomposition on galaxies observed with Integral Field Units.

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