Dynamical models of S0 and Sa galaxies

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Abstract. We present a set of detailed, self-consistent, isotropic dynamical models for disc galaxies. We start from the hypothesis that each galaxy can be decomposed in a bulge, following the $r^{1/4}$ law, and a disc with an exponential projected density profile; and that the isodensity surfaces of each component can be represented by similar concentric spheroids. Under these conditions we produce the rotational velocity and velocity dispersion profiles, after taking into account both the asymmetric drift effects and the integration along the line of sight.

The model is successfully applied to reproduce the stellar kinematic and photometry of the bulge of the 4 lenticular and early-type spiral galaxies NGC 4565, NGC 7814, NGC 5866 and NGC 4594. For these galaxies detailed stellar kinematical data are available at different positions across the galaxy.

The application of our models shows that: 1) For all the galaxies considered in this work, an isotropic model is able to reproduce the whole dynamical data. This is surprising in the special case of NGC 4565, for which previous models were unable to reproduce the velocity distribution without introducing strong anisotropies. 2) We do not need a dark mass halo to reproduce these data. This do not mean that a dark halo is not present, but just that its dynamical effects in these inner regions of the galaxies are negligible.

In our opinion, these results strongly support our guess that a complete dynamical model, including both a disc and a bulge component, is needed to understand the structure of the lenticular and Sa galaxies.

1. Introduction

The study of the distribution function of stars in galaxies may give strong constraints on the scenarios of formation of the galaxies. In the past, a particular attention has been paid to distinguish between isotropic cases, where the distribution function is characterized by only two classical integrals of motion (energy and angular momentum) and the anisotropic case, where a third (unknown) isolating integral is needed to explain the dynamics of the system.

A widely used tool to investigate the distribution function in elliptical galaxies is the classical $V/\sigma$ parameter, first introduced by Binney (1978). By applying this method to a large number of elliptical galaxies, it seems that two different kind of ellipticals may exist: elliptical galaxies fainter than $M_B=19.5$, 


with outer isophotes quite flat (disky), which are represented well by isotropic models, and bigger ellipticals \((M_B \leq 19.5)\), with isophotes more “boxy” and that cannot be explained by a model with isotropic velocity ellipsoid.

The structure and isotropy of the bulges of disk galaxies is far less clear: working on the same set of data, concerning fours S0 and Sa galaxies, Kormendy & Illingworth (1982) claims the isotropy of their bulges, while Whitmore, Rubin and Ford (1985) deduce the opposite conclusion. The fact that the same data may be interpreted in such different ways clearly demonstrates the ambiguity of the \(V/\sigma\) test when applied to the bulges.

On the other hand, the informations about the dynamical structures of the bulges could be crucial to determine if bulges can be considered as “dwarf ellipticals embedded in a gas disk”, as stellar populations, colors and luminosity profiles seems to suggest, or if they are a totally different class of objects.

2. The model

The main problems encountered dealing with models of bulges is the mixing of stars between disk and bulge and the mutual interaction of their potentials. These effects make harder the problem of to study the “pure” bulge component, that require some preliminary assumptions.
Figure 2. Rotational curves and velocity dispersion profiles for models with different values of the parameters $R_B/R_D$, $M_B/M_D$. Here we adopted the values $M_B/M_D = 1.36$ which, according to Simien and de Vaucouleurs (1986), corresponds to a typical Sa galaxy, while the $R_B/R_D$ parameter is ranging from 0.1 to 0.9 (models Sa1 through Sa9).

In modeling the elliptical galaxies it is common to assume that the isodensity surfaces are similar, concentric spheroids. This is in reasonable agreement with the shape of the observed isophotes, and has the great advantage to reduce the complexity of the dynamical equations. As said before, in such a case (ellipsoidal structures) the $V/\sigma$ test can be applied.

On the other hand, the isophotes of bulges in disk galaxies shows many different behaviors, such as wide change of flattening from the center of the galaxy to the outer regions. In this case, it is not possible to apply a simple ellipsoidal model. This problem is particularly presenting S0 and Sa galaxies, where the contributions of the bulge- and disk-components are comparable in strength.
Starting from a previous work of Galletta et al. (1990), we extended the ellipsoidal hypothesis to early-type disk galaxies, assuming that each galaxy may be “split” in two different components, having each one the following properties:

- The isodensity surfaces are similar concentric spheroids;
- The anisotropy parameter $\beta$ is constant throughout the galaxy (Here, we present only the case $\beta = 0$ of the isotropic model).
- The galaxy is rotating about the $z$-axis with velocity $V(R, Z)$, consistent with the self-gravity hypothesis.
- Each component has a constant $M/L$ ratio.

Under these hypothesis, the circular velocity due to the potential of each component is given by the well-known form (see Binney & Tremaine, 1986):

$$v_c^2(R, z) = -2\pi G \sqrt{1 - e^2} R \int_0^{\infty} \frac{\rho(m^2) \, d\tau}{(\tau + 1)^2 \sqrt{\tau + 1 - e^2}} \tag{1}$$

with $e$ the ellipticity of the component, and $m$ defined as

$$m^2 = \frac{R^2}{\tau + 1} + \frac{z^2}{\tau + 1 - e^2} \tag{2}$$

The density profile of the bulge is assumed to follow the $r^{1/4}$ law, while the disc (also “ellipsoidal”, but much flatter than the bulge) is described with an exponential density profile. In Fig. we present the photometric behavior of a typical galaxy constructed with these assumptions.

Since we are dealing with the inner kinematical properties of the galaxies, we deliberately discard any dark matter contribution to the overall potential, to limit the number of free parameters.

3. A library of models

A first goal of this work was to find out how kinematical (rotation and velocity dispersion) curves are changing when different bulge/disk ratios are assumed. Under the hypotheses described in the previous section, we produced several different models for different values of the parameters. In Fig. and in Fig. some of the obtained results are shown.

We want to stress out some points:

- The rotation curves of the galaxies on a plane perpendicular to the main galaxy plane become more and more linear at higher distance from this latter plane. This is in agreement with the available data for most of the observed spiral bulges;
- On the other hand, the asymmetric drift effect is very strong in the nucleus; this is due to the steep increase of density for the inner regions of the bulge (described as a pure $r^{1/4}$ model, without any core radius).
• The velocity dispersion profile is always not gaussian; more likely, it can be approximated by the sum of two gaussian curves.

![Diagram showing rotational velocity and velocity dispersion profile in a pure bulge model with a given axial ratio $b/a = 0.6$.](image)

**Figure 3.** Behavior of the rotational velocity and velocity dispersion profile in a pure bulge model with a given axial ratio $b/a = 0.6$. The different profiles are extracted at different vertical shifts $z$ from the major axis, as shown in the legend. Both the asymmetric drift effect and the line-of-sight projection are taken into account. All the models are seen edge-on and along the major axis.

4. **Comparison to the observations**

As a second goal, we applied our model to the galaxies studied by Kormendy and Illingworth (1982) and by Whitmore et al. (1985). In Tab. 1 the best-fit parameters found for all the four galaxies are shown. Our isotropic model fit fairly well the observations; this is particularly amazing in the case of NGC 4565 (Fig. 4), for which both the papers conclude that strong anisotropies in the velocity distribution are present.
Figure 4. The rotational curves and velocity dispersion profiles predicted by the model compared with the observations of Kormendy & Illingworth (1982). The label $\parallel$ means that the data are extracted along an axis which is parallel to the major axis, while the label $\perp$ label means parallel to the minor axis. All the velocities and velocity dispersions are in Km/sec. As described into the text, the model is described by one free parameter only.

The advantage of our model is that the only free parameter left is the $M/L$ ratio of the stellar component, if a detailed photometry is available. In such a case, the decomposition of the galaxy into a bulge and a disk component can be properly made, and we are able to predict the observed kinematics and photometry at any point of the galaxy on the sky simply by changing the value of this parameter. The diagnostic power of the model is, under these conditions, very high.
Table 1. Best-fit parameters of the model for the four early-type disk galaxies studied by Kormendy & Illingworth.

| Hubble Type | NGC 4565 | NGC 4594 | NGC 5866 | NGC 7814 |
|-------------|----------|----------|----------|----------|
|             | $L_B/L_D$ | $R_B$    | $R_D$    |
| Sb          | 0.538    | 50.59''  | 122.5''  | 30.17''  |
| Sa          | 11.5     | 18.9''   | 90''     | 32.2''   |
| S0          | 9        | 32.2''   | 41''     | 31.3''   |
| Sab         | 1.63     | 31.3''   | 117''    |          |
| $b/a_{B1}$  | 0.59     | 0.55     | 0.47     | 0.53     |
| D(Mpc)      | 18.9     | 19.3     | 18.4     | 25.0     |
| $M_B$       | -21.11   | -22.26   | -20.47   | -20.73   |
| $(M/L)_B$   | 9.5      | 7.5      | 7.       | 12.      |
| $M_{tot}$   | 4.17     | 8.6      | 1.72     | 4.04     |
| $(b/a)_B$   | 0.59     | 0.55     | 0.8      | 0.55     |
| $R_B/R_D$   | 0.7      | 1.0      | 1.0      | 0.487    |
| $M_B/M_D$   | 1.06     | 1.0      | 9.0      | 1.63     |

5. Conclusions

We developed a dynamical model to study the presence of isotropy in the bulges of early-type disk galaxies. The main advantage on previous works is that both the bulge and disk contributions may be properly taken into account, as well as the presence of the asymmetric drift and the integration along the line-of-sight.

The application of our model shows that:

- For all the galaxies considered in this work, an isotropic model is able to reproduce the whole dynamical data. This is surprising in the special case of NGC 4565, for which previous works suggested strong anisotropies in the velocity distribution.

- The model don’t needs a dark halo to reproduce these data. Its presence is, of course, possible, but its dynamical effects are negligible in the inner regions ($R \leq 1.2R_e$) of the considered galaxies. This result is in agreement with the conclusions of other authors (e.g. Persic & Salucci, 1995).

- The method seems to have a great diagnostic power if good kinematical data at different position angles are available and/or if many offset spectra have been taken.

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