Vertical structure in models of spiral and barred galaxies

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1 Phenomenology

Disk galaxies viewed edge-on reveal the vertical structure of their luminous matter. This structure varies from superthin, flattened, low surface brightness objects (as e.g. UGC 711), to high surface brightness galaxies with large spheroidal components in their central parts like the well known 'Sombrero Galaxy' (NGC 4594)[1].

In general, disk galaxies are considered to consist of three mass components: The disk, the bulge and the dark matter halo. At large radii, face-on disk galaxies typically have exponential luminosity profiles; the log of the surface brightness falls as a linear function of radius. Edge-on disks show that most of the luminosity comes from a rather thin component which is reasonably fit by a $L(z) = L_{(z=0)} sech^2(z/z_o)$ law, where z_o is the vertical scale height (van der Kruit & Searle 1982). A popular potential for 3D galactic disks that reasonably approximates the observed light distribution (combining the above laws) is the Miyamoto disk (Miyamoto and Nagai 1975). In cylindrical coordinates it has the form:

$$\Phi_d(R,z) = -\frac{G\,M_d}{\sqrt{R^2 + [\alpha + \sqrt{z^2+\beta^2}]^2}} \tag{1}$$

The parameter M_d refers to the disk mass, while the ratio β/α defines the thickness of the disk. Thus, by using this function we can approximate the light distribution either of an Sa (Fig. 1a), or of an Sc (Fig. 1b) galaxy. Evident from Fig.1 is that 3D

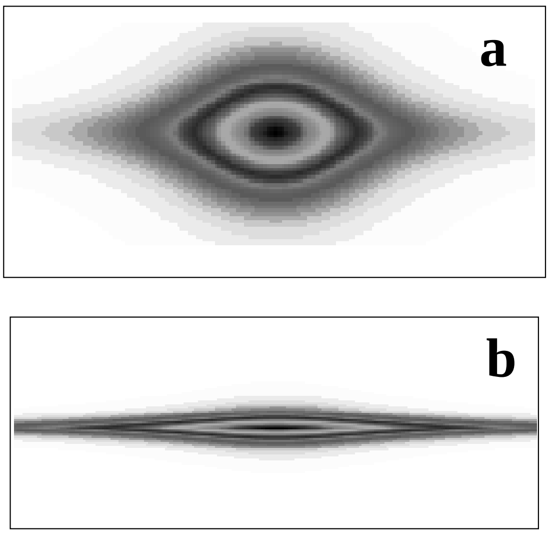

Figure 1: Density profiles of Miyamoto disks approximating observed profiles of type Sa (a), and Sc (b) disk galaxies.

disks may have a spheroidal-like central morphology without invoking an explicit bulge component. However, in many cases the luminosity profiles in the centers

[1] Images of these and the rest of the galaxies mentioned in the paper can be sought in the STScI Digitized Sky Survey at *http://stdatu.stsci.edu/cgi-bin/dss_form*

of galactic disks are characterized by the dominance of a spheroidal, the shape of which can be well–fitted by an $r^{1/n}$ law (bulges in early types being closer to de Vaucouleurs' law, and bulges of late types closer to exponential - Andredakis et al. 1995).

An interesting, frequently observed feature of the central morphology of galactic disks is their boxiness. Statistical studies (Lütticke et al. 2000a), show that 45% of the bulges of edge-on disc galaxies are box- or peanut shaped (hereafter b/p shaped). Typical for the b/p bulges is that their maximum thickness is not at the center of the galaxy like in usual $r^{1/4}$ spheroids, but 'at two points symmetrically spaced on either side of the center' (Burbidge & Burbidge 1959). Another difference from $r^{1/4}$-bulges and ellipticals is that b/p bulges rotate 'cylindrically', i.e. their observed rotation is independent of the height above the plane, while bulges and ellipticals show spherical rotation (Kormendy & Illingworth 1982). In that respect, b/p features have to be distinguished from the typical bulges. However, very often are called 'bulges' in the relevant literature since they dominate in the central parts of disk galaxies. There is also one more characteristic of b/p bulges related to their kinematics. Bureau & Athanassoula (1999) and Athanassoula & Bureau (1999), refining a method by Kuijken & Merrifield (1995), have shown that b/p bulges are associated with the appearance of an '8'-shaped profile in position-velocity diagrams. The method relies on the presence of x2 orbits (Contopoulos and Grosbøl 1989) in the bars of the galaxies. Several observational studies (Bureau & Freeman 1999, Lütticke et al. 2000b) associate the b/p structure with the bar.

2 Periodic orbits

A powerful tool for understanding observed structures in galaxies are the periodic orbits and their stability, calculated in static analytic potentials approximating the dynamics of real disk galaxies (Contopoulos 1994 and references therein). Stable periodic orbits are the building blocks for density models of galactic disks (Athanassoula et al. 1983) since they define families of trapped orbits around them. Trapped orbits are non-periodic, but oscillate about a periodic orbit, with a similar shape. Despite the fact that these models are not self-consistent, they give essential information about the dynamics of the disks; one can easily see the differences in the dynamical behavior introduced as the main parameters of the model vary.

The morphology of disk galaxies is characterized by the presence of patterns like spirals and bars. They are considered to be density waves rotating with their own pattern speed Ω_p. Ω_p is in general different from the angular velocity of the stars which depends on radius. In a first approximation the orbit of a star on the equatorial plane of a galactic potential can be considered as circular. However, stars are subject to radial and vertical oscillations and thus resonances can be defined between the radial and vertical frequencies and the angular velocity of the stars in the rotating with Ω_p frame of reference (for more details the reader may refer to standard textbooks as Binney and Tremaine 1987). Their location on the galactic disks is crucial for the dynamics of the system since it determines the families of periodic orbits existing and dominating in the potential under study. The description of the method used to calculate the stability of the periodic orbits in 3D systems can be found in Contopoulos & Magnenat (1985).

3 Discussion and Conclusions

Work in non-barred, spiral potentials has been done in models consisting of a Miyamoto disk, a logarithmic halo and a thick spiral of the form

$$V_s = -A\,R\exp(-\epsilon_s\,R)\left[\cos(2\frac{\ln(\frac{R}{R_s})}{\tan i} - 2\theta)\right]\mathrm{sech}^2\left(\frac{z}{z_s}\right) \tag{2}$$

where A is the amplitude of the perturbation, ϵ_s is the inverse radial scale length of the spiral and i is the pitch angle of the spiral (Patsis & Grosbøl 1996a;b)

Work in barred potentials has been done in models consisting of a Miyamoto disk, a Plummer bulge, and a 3D Ferrers bar, whose density $\rho(x)$ is:

$$\rho(x) = \begin{cases} \dfrac{105 M_B}{32\pi abc}(1-m^2)^2 & for \quad m \le 1 \\ 0 & for \quad m > 1 \end{cases}, \tag{3}$$

where

$$m^2 = \frac{y^2}{a^2} + \frac{x^2}{b^2} + \frac{z^2}{c^2}\ , \quad a > b > c, \tag{4}$$

a, b, c are the semi-axes and M_B is the mass of the bar component. (Patsis et al. 2002)

The basic conclusions concerning the 3D structure of disk galaxies are:

1. The observed edge-on profiles are the imprints of families of periodic orbits, that can be found in appropriately chosen Hamiltonian systems, describing the potential of the disk galaxy.
2. The profiles are determined by the presence or absence of the main vertical resonances.
3. Although kinematical studies (Bureau & Athanassoula 1999) suggest that b/p 'bulges' are associated with the presence of strong bars, orbital models indicate, that such edge-on profiles can be associated with weak bars in almost axisymmetric models as well, if the needed vertical resonances are present in the model (Fig.2). This is supported by recent N-body simulations (Athanassoula, private communication).
4. b/p profiles can be encountered in orbital models which lack radial and/or vertical 2:1 resonances.
5. The vertical profiles of the models are of 'stair-type'. The successive families that offer the skeletons for the 3D bars lower in general their mean heights as the energy at which they are bifurcated approaches corotation's energy.
6. The projection of the orbits of a family on the equatorial plane is confined inside certain limits. This means that moving on the characteristic towards corotation, a certain distance from the center is reached, where the mean radius of the orbits increases only due to increasing of the projection of the orbits on the axis perpendicular to the equatorial plane.
7. The family bifurcated from the central family of periodic orbits on the equatorial plane (x1 family) at the vertical 2:1 resonance, can easily build the observed 'X' structures in the centers of some galaxies *if* its orbits reaching relatively low heights above the equatorial plane are not complex unstable. However, the latter case appears for a large area of the parameter space with realistic values.

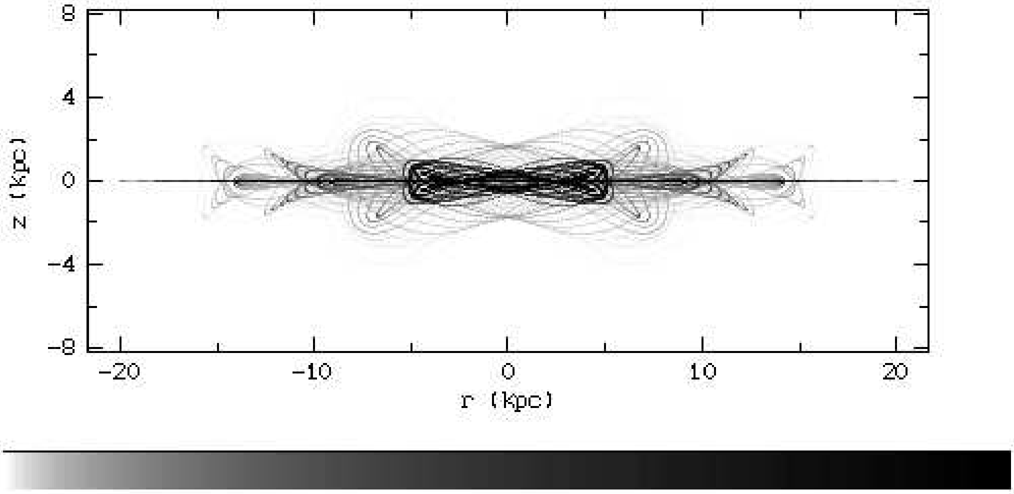

Figure 2: A b/p profile of a non-barred model based on stable periodic orbits. The orbits are weighted (Patsis & Grosbøl 1996b). The importance of each orbit for a density model based on non-periodic orbits trapped around stable ones, is proportional to its darkness and the used grey-scale is linear as indicated by the bar at the bottom of the figure.

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