Boxy/peanut ‘bulges’: comparing the structure of galaxies with the underlying families of periodic orbits

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ABSTRACT
The vertical profiles of disc galaxies are built by the material trapped around stable periodic orbits, which form their ‘skeletons’. Therefore, knowledge of the stability of the main families of periodic orbits in appropriate 3D models enables one to predict possible morphologies for edge-on disc galaxies. In a pilot survey we compare the orbital structures that lead to the appearance of ‘peanut’- and ‘X’-like features with the edge-on profiles of three disc galaxies (IC 2531, NGC 4013 and UGC 2048). The subtraction from the images of a model representing the axisymmetric component of the galaxies reveals the contribution of the non-axisymmetric terms. We find a direct correspondence between the orbital profiles of 3D bars in models and the observed main morphological features of the residuals. We also apply a simple unsharp masking technique in order to study the sharpest features of the images. Our basic conclusion is that the morphology of the boxy ‘bulges’ of these galaxies can be explained by considering disc material trapped around stable 3D periodic orbits. In most models, these building-block periodic orbits are bifurcated from the planar central family of a non-axisymmetric component, usually a bar, at low-order vertical resonances. In such a case, the boxy ‘bulges’ are parts of bars seen edge-on. For the three galaxies we study, the families associated with the ‘peanut’ or ‘X’-shape morphology are probably bifurcations at the vertical 2/1 or 4/1 resonance.

Key words: dust, extinction – galaxies: kinematics and dynamics – infrared: galaxies – infrared: ISM.

1 INTRODUCTION
Patsis & Grosbøl (1996), Patsis et al. (2002a), and Patsis, Skokos & Athanassoula (2002b, hereafter PSA) have presented boxy orbital profiles of 3D time-independent models of disc galaxies. These profiles have been built by combinations of stable 3D orbits belonging in most cases to families of periodic orbits bifurcated from the planar x1 family (see e.g. Contopoulos 2002, or Contopoulos & Grosbøl 1989) at the vertical n/1 resonances. The most efficient dynamical mechanism for introducing vertical resonances in a system is the presence of non-axisymmetric components, especially bars.

Vertical profiles of 3D bars have been constructed by PSA, based on the orbital analysis of 3D Ferrers bars (Pfenniger 1984, 1985; Skokos, Patsis & Athanassoula 2002a,b). A profile of a single family includes stable orbits in a range of ‘energies’ (Jacobi constants – $E_j$). In order to construct a family profile it is necessary to know its stable orbits. Out of this library of stable periodic orbits, any subgroup that helps in matching the observed morphological structure can be chosen. Every family has its own characteristic orbital profile, and the profiles of a given family in different models are similar. Combinations of the profiles of several families of a model comprise a model profile. Particularly useful representations of the orbital profiles that allow comparisons with real galaxies, or with snapshots of N-body simulations, are their weighted images (PSA). The advantage of these images is that they show the relative importance of every orbit in a profile. They also show the details of the morphology in locations where more than one orbit contributes. The images are composed of periodic orbits weighted by the mean density of the model at the points visited by the orbit. Along each orbit, points are picked at equal time-steps. The density of the model is calculated at each of these points, and the mean density is taken as the weight of the orbit. Having constructed images for every orbit (normalized over its total intensity), it is possible to combine them to build a profile for a family of orbits. For the profile of a family, orbits equally spaced in their mean radius are used.

The basic conclusions of the orbital analysis relevant to the present study are as follows.

(i) The morphology supported by the composite orbital profile of a family may differ from the morphology of the individual periodic orbits calculated at a particular $E_j$. Thus, in order to obtain the...
The backbone of a structure to be compared with the morphology of a galaxy, it is necessary to know the evolution of the shape of the stable orbits of a family as a function of $E_0$.

(ii) The radial extent of the edge-on profile of an orbital 3D family is usually confined within a radius corresponding to a certain $E_0$ value. Orbits with a Jacobi constant larger than this $E_0$ increase their size by increasing practically only in the vertical dimension, and this leads to models with stair-type edge-on profiles (for more details see Patsis et al. 2002a).

To these two points, it should be added that it is the presence of the vertical resonances and not the detailed kind of perturbation in the models that shapes the boxiness of the orbital profiles. However, ‘X’-like features such as those we discuss here are typical of strong bar components.

Recently, unsharp masking techniques applied to images of galaxies (Aronica et al. 2003, 2004; Bureau et al. 2004) as well as to images of snapshots of $N$-body simulations (Athanassoula 2005a,b) have shown excellent agreement between the image morphologies and what is predicted by the orbital theory in PSA. In particular, Aronica et al. (2003) compared the image of ESO 597-036 after unsharp masking with a model in PSA. They found, besides a conspicuous ‘X’-shape feature in the central part, surface brightness enhancements along the equatorial plane of the galaxy. Both features have counterparts in the orbital models and can be explained by material trapped around stable periodic orbits. Similar features are indicated by Aronica et al. (2004) for ESO-443G042 and by Bureau et al. (2004) for NGC 128. The comparison of features between orbital and $N$-body models shows agreement in even finer details. In both papers by Athanassoula (2005a,b), it is possible in the edge-on views of the models to find, besides ‘X’-like features, density enhancements on the equatorial plane and features resembling ‘parentheses’ (see, for example, fig. 6 in Athanassoula 2005a). This is a strong indication that a large percentage of the material in the $N$-body simulation follows orbits around the families bifurcated at the vertical $n/1$ resonances with small $n$.

In the present paper we apply two image-processing techniques to the images of three edge-on disc galaxies with boxy ‘bulges’ in order to detect structures similar to those predicted by orbital theory. We focus our attention on the structures observed in the central regions of IC 2531, NGC 4013 and UGC 2048 (NGC 973). First we subtract from the $I$-band images of the galaxies an axisymmetric model developed by Xilouris et al. (1997) to describe the smooth distribution of stars and dust in these objects. The models are used to isolate the non-axisymmetric term in the profiles of the galaxies. This term is expected to reflect in a straightforward way the presence of vertical resonances (PSA). The second technique we apply is just a Gaussian filtering (unsharp masking) on the images. In Section 2 we give information about the observations of the galaxies, in Section 3 we describe the image-processing techniques, in Section 4 we give the results of the image processing that we performed, and finally we discuss our results and present our conclusions in Section 5.

### 2 OBSERVATIONS

The observations and the data reduction of the galaxies analysed in this study are presented in Xilouris et al. (1997) and Xilouris et al. (1999). We briefly summarize them here.

Observations of the galaxies UGC 2048 and NGC 4013 were made at Skaniasa observatory in Crete, using the 1.3-m telescope with a Thomson 1024 × 1024 CCD camera installed at the prime focus of the f/7.7 Ritchey–Cretien telescope. The 19-μm pixels of this camera correspond to 0.39 arcseconds on the sky, giving a total field of view of $6.7 \times 6.7$ arcmin$^2$. IC 2531 was observed with the 1-m Australian National University telescope (ANU) at Siding Spring Observatory. The CCD camera in this case is an EEV 576 × 380, giving a pixel size of 0.56 arcseconds at the f/8 Cassegrain focus. The $I$ passband comparable to that of the Cousins photometric system is used in both cases. The exposure times are 20, 25 and 25 min for UGC 2048, NGC 4013 and IC 2531 respectively.

In Table 1 we summarize the basic observational properties of the galaxies as well as some characteristic parameters describing the axisymmetric stellar and dust components (see Section 3). For the samples of the galaxies in Xilouris et al. (1997) and Xilouris et al. (1999) for which models for the axisymmetric light and dust distribution exist, we have selected three with boxy profiles for application of our image-processing techniques.

| Name      | Pixel size (arcsec) | Exp. time (min) | $D$ (Mpc) | Inclination (degrees) | $h_s$ (kpc) | $h_d$ (kpc) | $z_s$ (kpc) | $z_d$ (kpc) | $R_e$ (kpc) | $I_s$ (mag arcsec$^{-2}$) | $I_b$ (mag arcsec$^{-2}$) |
|-----------|---------------------|-----------------|-----------|-----------------------|-------------|-------------|-------------|-------------|-------------|-------------------------|-------------------------|
| UGC 2048  | 0.39                | 20              | 63        | 89.6                  | 11.0        | 16.5        | 1.0         | 0.57        | 2.4         | 18.4                    | 9.1                     |
| NGC 4013  | 0.39                | 25              | 12        | 89.6                  | 1.8         | 2.6         | 0.2         | 0.10        | 1.6         | 17.3                    | 10.5                    |
| IC 2531   | 0.56                | 25              | 22        | 89.7                  | 5.0         | 8.4         | 0.4         | 0.20        | 1.6         | 18.2                    | 11.0                    |

### 3 DETERMINING THE UNDERLYING STRUCTURE OF THE GALAXY

Disc galaxies are not axisymmetric systems. Their surface brightness can be described as the sum of an axisymmetric and a perturbing term. The latter refers to the presence of spirals or bars. The axisymmetric component is the most important and can be described by simple smooth functions (such as axisymmetric exponential discs for the stars and the dust in the plane of the galaxy and a de Vaucouleurs $R^{1/4}$ law for the bulge). Besides the global perturbations there are clumps and star-forming regions that cause deviations from smoothness locally. In the present paper we are interested in the global non-axisymmetric components.

Studying the smooth distributions is not only instructive (a very good description of the galaxy is obtained with as few parameters as possible) but can also be very helpful in uncovering features resulting from non-axisymmetric components (e.g. bars). This is achieved by subtracting the axisymmetric model from the image of the galaxy. If the axisymmetric model is able to describe the large-scale structure well, then, with this method, what it left, namely the residuals, will indicate features that mainly have to do with either the non-smooth distribution of the dust (seen as absorption features) or the non-axisymmetric component of the stars (seen as excess of starlight). Assuming a constant mass-to-light ratio ($M/L$), this light excess will indicate regions of enhanced stellar density and will be comparable with the orbital models. Good agreement will indicate...
that large percentages of stars are trapped around stable periodic orbits.

The model that we use is described in great detail in Xilouris et al. (1997). The stellar emissivity (luminosity per unit volume) that we use consists of an exponential (in both radial and vertical directions) disc, and a bulge described by the $R^{1/4}$ law, namely

$$L(R, z) = L_s \exp \left( -\frac{R}{h_s} - \frac{|z|}{z_s} \right) + L_b \exp(-7.67 B^{1/4} B^{-7/8}),$$

with $h_s$ and $z_s$ being the scalelength and scaleheight of the disc, and

$$B = \sqrt{R^2 + z^2 (a/b)^2}/R_e,$$

where $R_e$ is the effective radius of the bulge, and $a$ and $b$ are the semimajor and the semiminor axis respectively. Here $L_s$ and $L_b$ are the normalization constants for the stellar emissivity of the disc ($L_s$) and the bulge ($L_b$). The central value for the surface brightness of the disc and the bulge, if the model galaxy is seen edge-on and there is no dust, are given by $I_s = 2L_s h_s$ and $I_b = 5.12 L_b R_e$.

For the extinction coefficient we use a double exponential law, namely

$$\kappa_\lambda (R, z) = \kappa_\lambda \exp \left( -\frac{R}{h_\lambda} - \frac{|z|}{z_\lambda} \right),$$

where $\kappa_\lambda$ is the extinction coefficient at wavelength $\lambda$ at the centre of the disc, and $h_\lambda$ and $z_\lambda$ are the scalelength and scaleheight, respectively, of the dust.

The radiative transfer model that we have used is the one described by Kylafis & Bahcall (1987) (see also Xilouris et al. 1997). The results are summarized in Table 1, where we give the values of the most important parameters in the best fittings.

The unsharp masking used standard ESO MIDAS commands. First we apply to the image a Gaussian filter with a radius of 5 pixels around the central pixel, and with mean and sigma values of 5 and 2 pixels, respectively, in both directions. With this procedure, a blurred image of the galaxy is created. Then, after subtracting the filtered from the original image, the residual indicates the presence of the sharpest features on the images.

4 RESULTS

In Fig. 1 we show the residual maps created by subtracting the model images of Xilouris et al. (1997, 1999) from the observed images of the three galaxies [NGC 4013 (a), IC 2531 (b) and UGC 2048 (c)]. The images have been rotated so that the major axis of the galaxies is along the large dimension of the frame. The difference between the models and the observations are relatively small, indicating the ‘perturbation’ character of the non-axisymmetric components (on average 15 per cent – Xilouris et al. 1997, 1999). However, this procedure offers a straightforward tracer exactly of this excess light that we are interested in. The main characteristic feature is an ‘X’-shaped structure revealed in the central parts of the galaxies. By comparing the residuals with the full images of the galaxies it can be seen that the ‘X’ features are in the same regions as the boxy bulges. The images after unsharp masking show sharp features that resemble the wings of an ‘X’. This can be seen in Fig. 2 for the above galaxies. Characteristic contours underline the main structure observed. In this case we can better distinguish the highest-contrast features. Again they are located in the regions occupied by the boxy bulges. They should be compared with features expected in the central parts of 3D bars viewed almost edge-on. The ‘X’-shape is encountered only in models for bars, while boxy bulges in general can be found also in non-barred models (Patsis et al. 2002a).
Figure 2. The result of unsharp masking on the images of (a) NGC 4013, (b) IC 2531 and (c) UGC 2048. ‘X’-shaped features similar to the structures predicted by the orbital models can be found in all three cases. Arrows indicate breaks of the ‘X’ wings. Colour coding is given below (a).

5 DISCUSSION AND CONCLUSIONS

Both image-processing techniques revealed a kind of ‘X’ structure in the central components of the three edge-on galaxies with boxy profiles that we studied. In Fig. 1, which gives the residuals after subtracting a Xilouris et al. (1997) model, the overall shape of the non-axisymmetric component can be seen. The unsharp masking in Fig. 2 shows the high-intensity features of the ‘bulges’ more clearly: they emerge out of the equatorial plane as distinct branches.

In most models in PSA, an ‘X’ is supported by material trapped around x1v1 orbits (Skokos et al. 2002a); that is, by stable 3D orbits introduced in the system at the vertical 2/1 resonance. There are, however, other 3D families as well, which could support straight-line segments emerging out of the equatorial plane in the edge-on projections of the orbital models. Such is the case of x1v5, according to the nomenclature of Skokos et al. (2002a), which is a family born at the vertical 4/1 resonance. This family has been associated with boxy central components by Pfenniger (1985). A typical orbital profile is given in fig. 7(a) of PSA.

In models (orbital or N-body), a visual difference can be found in a comparison of the side-on views. The distance between the wings of the ‘X’ feature in the x1v5 case is larger than the distance of the corresponding wings in x1v1 profiles. The difference can be seen in Fig. 3, which shows in (a) a side-on typical x1v1 profile and in (b) a profile dominated by the presence of the x1v5 family. They correspond to models D and B in PSA. As mentioned in the Introduction, there is a certain value of $E_j$, beyond which the orbits of a family grow practically only in the z-direction. So, for each family, there is a maximum radius on the equatorial plane within which the projections of its orbits are confined. In the side-on views we can measure the length of the projection along the major axis of the bar. In the two specific examples given here, the projection of the x1v1 orbits on the major axis of the bar in Fig. 3(a) corresponds roughly to a length of 45 per cent of the longest bar supporting orbits, i.e. the length of the bar in our orbital model. In Fig. 3(b), however, this percentage reaches almost 90 per cent. Unfortunately, this criterion cannot in general apply to the images of real galaxies because we are missing the essential information about the orientation of the boxy structure with respect to the line of sight. Thus, at the level of the current analysis, we cannot point to a single vertical resonance and attribute an observed morphological feature to it. A galaxy may lack...
a vertical 2/1 (or even 3/1) resonance, in which case material may be trapped by stable orbits bifurcated at the vertical 4/1 resonance. The corresponding profile in such a case will look like what we see in Fig. 3(b). It consists of stable orbits of the following families: (i) x1v5, (ii) a bifurcation of it, and (iii) z3.1s (PSA).

Another point that should be mentioned is the inward bending or break of the wings of the ‘X’ close to their maximum height above the equatorial plane. According to the orbital models this can be explained by the fact that the orbits of a family increase their size practically only in the vertical direction beyond a certain $E_i$ value. In Fig. 3(a) arrows denote these breaks for the x1v1 profile. This is, however, expected to happen to the profiles of other families if they are populated by orbits with high energies ($E_i$) for a characteristic case, see PSA, fig. 18). This tendency can be observed at the wings of the ‘X’ features in Fig. 2(a) (NGC 4013) and Fig. 2(c) (UGC 2048). These breaks are indicated with arrows.

The main conclusion of the present study is that the careful subtraction of axisymmetric components from the profiles of three edge-on disc galaxies (NGC 4013, IC 2531 and UGC 2048) reveals an ‘X’-like morphology, which indicates the presence of a bar. With this method we can isolate the light coming from the non-axisymmetric components. The similarity of these components to the morphology of the orbital profiles is a strong indication that the boxy ‘bulges’ of these three galaxies are parts of bar structures observed edge-on. If the ‘X’-like structure of the residuals results from stars trapped around stable periodic orbits, then we expect the presence of sharp features (the wings of the ‘X’) inside the bar region. By applying unsharp masking to the images we find, as predicted by the orbital models regions, sharp features. The two methods are complementary. The unsharp masking does not give any information about the overall shape of the non-axisymmetric component. It shows, however, that in the regions where we see the residuals we have the expected sharp features. These features show a nice correspondence with the dense parts of published orbital models (see PSA, figs 1a, 3b, 7a and 9a). These techniques, and especially the study of the residuals after subtracting axisymmetric models, should be applied to a large sample of galaxies in order to estimate the frequency of these features in the profiles of boxy edge-on galaxies.

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