Comparing peanut–shaped 'bulges' to N–body simulations and orbital calculations

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Abstract. We present a near-infrared K_n–band photometric study of edge–on galaxies with a box/peanut–shaped 'bulge'. The morphology of the galaxies is analysed using unsharp masking and fits to the vertical surface brightness profiles, and the results are compared to N-body simulations and orbital calculations of barred galaxies. Both theoretical approaches reproduce the main structures observed.

Keywords: galaxies: evolution — galaxies: structure — galaxies: photometry

1. Introduction

Box/peanut (b/p) shaped 'bulges' are frequently observed in edge–on galaxies (see Fig. 1; Lütticke, Dettmar, and Pohlen 2000a and references therein). They are also seen in many N–body simulations of barred disks which display a vertical thickening of the bar during its evolution, with a projected shape similar to the observed b/p structures (e.g. Combes, Debbasch, Friedli et al. 1990; Athanassoula and Misiriotis 2002, hereafter AM02). The works of Merrifield and Kuijken (1999) and Bureau and Freeman (1999, hereafter BF99) support this view observationally. They analysed ionised gas position–velocity diagrams of edge–on spirals using the method described in Kuijken and Merrifield (1995) and Athanassoula and Bureau (1999). Kinematic bar signatures were detected in essentially all the galaxies showing a b/p feature. In a large sample of galaxies ($N = 60$), the photometric link between bars and b/p 'bulges' was demonstrated reliably for the first time by Lütticke, Dettmar, and Pohlen (2000b).

2. Data

We analysed near-infrared K_n–band photometry of a sample of 33 edge–on galaxies, 30 of which were studied kinematically by BF99. The

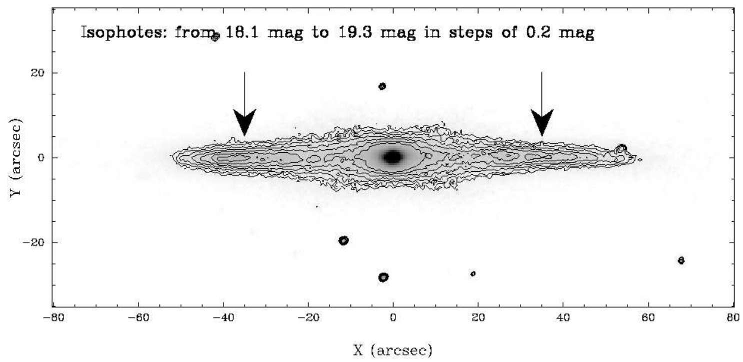


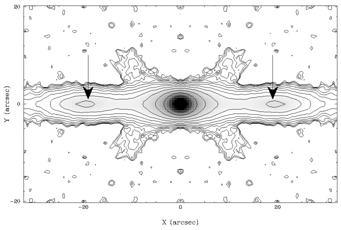
Figure 1. Image of ESO 443 -042, a galaxy with a peanut–shaped 'bulge' in the inner 15 arcsec. Isophotes are overlaid on a grayscale rendition of the K_n-band image. The arrows point to local maxima of the surface brightness along the major axis.

objects are characterised by their bulge morphology, with 24 galaxies showing a b/p structure and the remaining a more spheroidal shape.

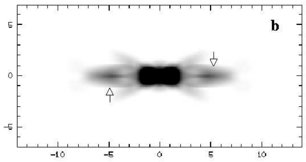
We applied the technique of unsharp masking to our images to analyse their morphology. The results were then compared to edge–on projections of b/p structures obtained from orbital calculations and presented in Patsis, Skokos, and Athanassoula (2002, hereafter PSA02). In addition, to quantify the b/p structure in an objective manner, we studied our sample with the fitting method described by AM02, where generalised gaussians of the form $I = I_0 \exp[-(z/z_0)^\lambda]$ are used to fit the vertical surface brightness profiles of the disk/bar components of the simulations. To minimise the influence of the bulge in our images (as the bulge was excluded from the N–body profiles), we apply a magnitude cut to the fit in the inner parts of the galaxies.

3. Results

Most of the original (e.g. Fig. 1) and unsharp-masked (e.g. Fig. 2a) images show local surface brightness enhancements along the major axis on both sides of the central regions. The positions of these characteristic enhancements coincide with the ends of the bar (determined kinematically) and are observed in 18 of the 24 galaxies showing a b/p 'bulge', but in only 1 of the remaining 9 non–b/p galaxies. A possible explanation is an inner ring delineating the ends of the bar, since the edge–on projection would enhance the surface brightness at those positions (see AM02). A similar effect can also occur in the case of spiral arms starting at the bar's ends, but an alternative explanation has been proposed by PSA02, who explain the enhancements by a combination



a) Unsharp masking of ESO 597 -036.



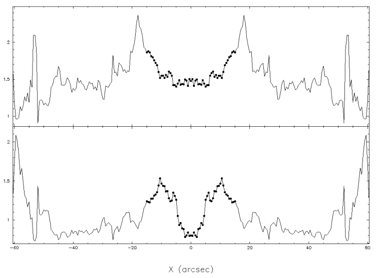
b) Model A2 of PSA02.

Figure 2. **a)** Unsharp-masked image of ESO 597 -036. The galaxy was symmetrised with respect to both symmetry axes to improve the signal–to–noise ratio and a median filter of 16.5 arcsec was applied. The 'branches' of the X–feature originate well outside of the galactic center. Note again the local density enhancements in the equatorial plane, at a projected radius of 20 arcsec from the centre. **b)** Model A2 from PSA02. This side–on profile is built from the superposition of the x2v1, x1v1, x1v3, and x1v4 families of periodic orbits. The arrows indicate local density enhancements. Reproduced from PSA02 with the permission of MNRAS published by Blackwell Science.

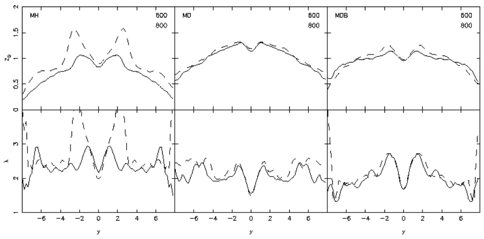
of four different orbit families and the projection of material trapped around stable periodic orbits close to the bar's ends (Fig. 2b).

In addition to the surface brightness maxima, the apparent X–shape of b/p 'bulges' is clearly seen in the unsharp–masked images of the sample galaxies (see, again, Fig. 2a). Two types of X–shapes are present in our sample. The first type is characterised by the fact that the 'branches' of the X–feature originate at the center of the galaxy. In the other cases, the branches seem to originate well outside of the central regions (e.g. Fig. 2a). PSA02 also find these two separate morphologies in their work. For example, their model A2, with a relatively slow pattern speed, reproduces an X–morphology with branches emerging from the centre of the galaxy (Fig. 2b), whereas their model D, characterised by a very strong bar, has an X–feature with branches starting away from the central bulge (as in Fig. 2.a). A comparison with unsharp–masked images is justified here because PSA02's models include only periodic orbits, which are representative building blocks of the galaxies but not a self-consistent model.

The quantification of the peanut structure of ESO 443 -042 by vertical fits (Fig. 3a) shows a qualitative similarity with the fits of model MH in AM02 (massive halo, time 800; Fig. 3b). In both cases the scaleheight z_0 and the shape parameter λ show a clear peak at or near the maximal extension of the b/p structure. But the two peaks are in fact at slightly different radii; in both the observations and the N–body simulations, we can observe that the peaks of the shape parameter λ are closer to the center than those of the scaleheight z_0. The analysis of the fits for the entire sample is ongoing.



a) Vertical fits to ESO 443 -042.



b) Vertical fits to AM02's models.

Figure 3. **a)** Vertical fits to ESO 443 -042. Generalised gaussians were fit to vertical cuts of a symmetrised image. The inner parts are excluded from the fit to minimise the bulge contribution and values obtained at those positions are marked with dots. Note that despite the exclusion of the central parts the bulge still contributes somewhat within 15 arcsec. The upper panel shows the scaleheight z_0 and the lower one the shape parameter λ, both as a function of the projected radius. **b)** Same as a) but for the N–body simulations discussed by AM02. Each column corresponds to a different model. From left to right: model MH (massive halo), MD (massive disk), and MDB (massive disk with bulge). Note, however, that in the last case the bulge was not taken into account in the fits. Solid and dashed lines correspond to times 600 and 800, respectively. Reproduced from AM02 with the permission of MNRAS published by Blackwell Science.

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