THREE-DIMENSIONAL BAR STRUCTURE AND DISC/BULGE SECULAR EVOLUTION

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Abstract *K*n-band imaging of a sample of 30 edge-on spiral galaxies with a boxy or peanut-shaped (B/PS) bulge is discussed. Galaxies with a B/PS bulge tend to have a more complex morphology than galaxies with other bulge types, unsharp-masked images revealing structures that trace the major orbit families of three-dimensional bars. Their surface brightness profiles are also more complex, typically containing 3 or more clearly separated regions, including a shallow or flat intermediate region (Freeman Type II profiles), suggestive of bar-driven transfer of angular momentum and radial redistribution of material. The data also suggest abrupt variations of the discs' scaleheights, as expected from the vertical resonances and instabilities present in barred discs but contrary to conventional wisdom. Counter to the standard 'bulge + disc' model, we thus propose that galaxies with a B/PS bulge are composed of a thin concentrated disc (a disc-like bulge) contained within a partially thick bar (the B/PS bulge), itself contained within a thin outer disc. The inner disc most likely formed through bar-driven processes while the thick bar arises from buckling instabilities. Both are strongly coupled dynamically and are formed mostly of the same (disc) material.

1. Introduction

Bulges are traditionally viewed as low-luminosity elliptical galaxies, suggesting a rapid formation dominated either by mergers/accretion (e.g. Searle & Zinn 1978) or possibly by dissipative gravitational collapse (e.g. Eggen et al. 1962). Those ideas have come under increasing criticism, however, and competing models where bulges grow secularly (i.e. over a long timescale and in relative isolation) are now widely discussed, many of them bar-driven (e.g. Pfenniger & Norman 1990; Friedli & Benz 1995).

We focus here on the identification of most boxy and peanut-shaped (B/PS) bulges in edge-on spiral galaxies with part of the bars of barred spirals. N-body simulations clearly show that, whenever a disc forms a bar, a B/PS bar/bulge develops soon after (e.g. Combes & Sanders 1981; Combes et al. 1990). True peanuts are seen with the bar nearly side-on while boxier/rounder shapes are seen when the bar is closer to end-on. This view is supported by the incidence of B/PS bulges in edge-on spirals (e.g. Lütticke et al. 2000a) and by the ionized-gas and stellar kinematics of discs harbouring a B/PS bulge (e.g. Kuijken & Merrifield 1995; Bureau & Freeman 1999; Chung & Bureau 2004).

Following recent work by Lütticke et al. (2000b), we present here additional evidence for the above scenario based on Kn-band imaging of a sample of well-studied nearby edge-on spiral galaxies with a B/PS bulge. The observations and results are described more deeply in Bureau et al. (2006) and Athanassoula et al. (2006).

2. Images

The 30 edge-on spiral galaxies of Bureau & Freeman (1999) and Chung & Bureau (2004), 24 of which have a B/PS bulge (the rest constituting a control sample), were observed at Kn-band using CASPIR on the 2.3m telescope at Siding Spring Observatory. Both a standard image and numerous unsharp-masked images (enhancing local extrema) were produced for every galaxy. Examples are shown in Figure 1 for a B/PS bulge and a nearly bulgeless galaxy. Compared to other bands, Kn is least hampered by dust and best traces the dominant Population II stars, sharpening the B/PS and associated features.

The unsharp-masked images highlight pervasive complex morphological structures, such as centered X features, off-centered X features, secondary maxima along the major-axis, elongated minor-axis extrema, spiral arms, etc (see Fig. 1). Most importantly, except for the minor-axis extrema, those structures are much more prevalent in galaxies with a B/PS bulge. For examples, 88% of galaxies with a B/PS bulge have either a centered or off-center X feature, while only 33% of the control galaxies do, with identical fractions for secondary major-axis maxima. The contrast between the main and control samples would in fact be even greater if the latter was not contaminated by weak B/PS bulges. Although the accretion of external material can give rise to centered X-shaped features (e.g. Hernquist & Quinn 1988), it is unlikely that long-lasting off-centered X could be produced, and those are the majority of the features observed in our sample. The orbital structure of 3D bars offers a more attractive, simple and unifying and explanation.

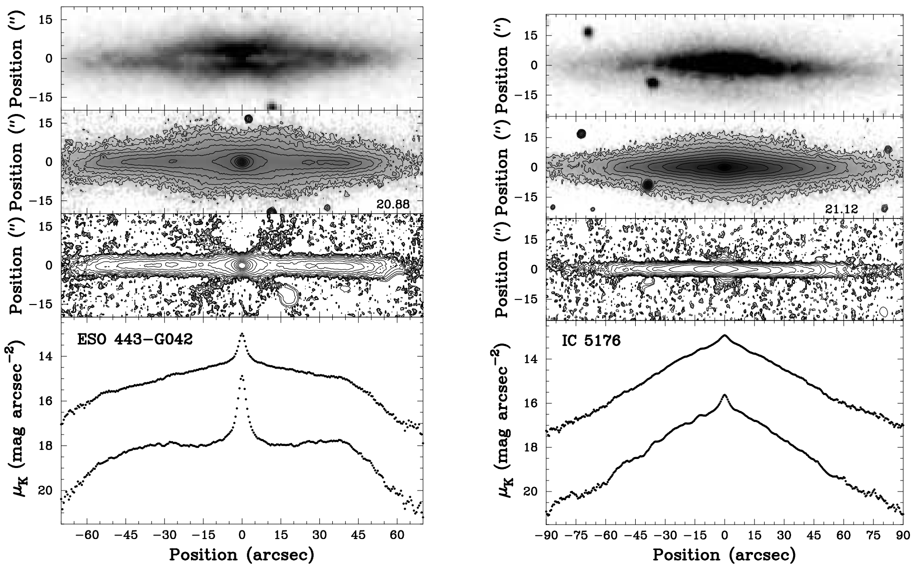

Figure 1. Images and surface brightness profiles of the galaxies ESO443-G042 (left), with a B/PS bulge, and IC5176 (right), with a nearly pure disc. From top to bottom, each panel shows first a DSS image of the galaxy, second our *K*n-band image, third an unsharp-masked *K*n-band image, and last the major-axis (fainter) and vertically-summed (brighter) surface brightness profiles, all spatially registered.

The most important orbit families in 3D bar models are those of the x_1 tree, elongated parallel to the bar and located within corotation. This includes the x_1 family itself (restricted to the equatorial plane) and other families bifurcating from it at vertical resonances. The morphological features observed can be reproduced by superposing orbits of the appropriate shapes, as done by Patsis et al. (2002). This is particularly true of the (off-)centered X features which, depending on the model (mass distribution and pattern speed) and viewing angle, can *both* arise from orbit families extending vertically out of the equatorial plane. The same orbits can give rise to a number of maxima along the major-axis, similar to the secondary maxima observed. Those generally occur at larger radii than the X features and near (but within) the ends of the bar. An analogous explanation is that the secondary maxima are the edge-on projections of the inner rings present in a large fraction of barred spiral galaxies (e.g. Buta 1995) and predicted to form under the influence of bars in gas-rich and gas-poor discs (e.g. Schwartz 1981; Athanassoula & Misiriotis 2002). Unsharp-masking of barred N-body simulations also provides a perfect match to the variety of features observed, strengthening the link between them and edge-on bars (Athanassoula 2005).

3. Surface Brightness Profiles

We also extracted from our images standard major-axis surface brightness profiles and profiles summed in the vertical direction (as if the galaxies were infinitely thin). From axisymmetric face-on galaxies, we would generally expect the profiles to show only two distinct regions: a first steep region at small radii, associated with the bulge, and a second exponential region at larger radii, associated with the disc. Such profiles are however rare in our data, especially along the major-axis.

In particular, the profiles of galaxies with a B/PS bulge are again more complex than those of the control sample, in that they typically contain more distinct regions separated by clear radial breaks. For example, 96% of the galaxies with a B/PS bulge have a major-axis profile with an additional region at intermediate radii, where the profile is very shallow, even flat or slightly rising (Freeman Type II profile; see Fig. 1). The fraction for the control sample is only 50%, and the contrast between the two samples would again be sharper if they had been better selected.

Those shallow intermediate regions are particularly important as they suggest a third photometric/morphological component at moderate radii, inconsistent with a classic axisymmetric bulge + disc model. Both the central peak and the flat intermediate region are however consistent with a *single* bar viewed edge-on, with no need for a classic bulge. Indeed, Bureau & Athanassoula (2005) followed the evolution of the major-axis profile in barred N-body simulations viewed edge-on, and they convincingly showed that bar formation and evolution is associated with the buildup and continued growth of a dense central region, which would normally be identified with a bulge, and with the formation and gradual flattening of an intermediate region, in addition to the outer exponential disc. The intermediate region extends to the end of the bar, well beyond the central peak and the thickest part of the bar, as observed.

As expected from the elongated boxy/peanut shape of the bar in simulations, the observed ratio of the length of the thickest part of the bulge (or the central peak) to that of the flat intermediate region is also generally larger in peanut-shaped bulges than in boxy ones. There is however much variety, and likely many causes for it. Even so, the scatter in the ratio may well be dominated by the range of bar strengths in the sample, rather than by the range of viewing angles, as also suggested by the data of Lütticke et al. (2000b). The small ratios observed in strong peanut-shaped bulges (see Fig. 1) can then be explained only if the central peak and the thick part of the bulge are shorter in stronger bars. This is natural in barred models if the central peak is a disc-like bulge limited by the outer inner Lindblad resonance (e.g. Athanassoula 1992).

4. Bar-Driven Evolution

Athanassoula (2003) showed that much of the bar-driven evolution in discs is due to a transfer of angular momentum from the inner (barred) disc to the outer disc and halo, leading to a *radial* redistribution of matter. The majority of vertically-summed surface brightness profiles, best suited to isolate those effects, indeed show 3 or more clearly separated regions, while only one of the control galaxy does. Collapse or accretion/merger scenarios can not straightforwardly create those radial breaks or explain their spatial correlation with the ionized-gas and stellar kinematics. But if bar-driven scenarios are right, the break at the end of the intermediate region should mark the bar's end. Comparison shows that it indeed occurs where the rotation curve flattens, normally associated with the end of the bar. The break also coincides with the inner ring, when visible. As inner rings occur near the inner 4:1 and corotation resonances (e.g. Schwartz 1981), our galaxies are consistent with harbouring fast bars, as do most galaxies (e.g. Gerssen et al. 2003).

To probe the *vertical* redistribution of material predicted by bar buckling scenarios, we must compare the major-axis and vertically-summed profiles. If the stellar scaleheight was constant with radius, the two profiles would have the same functional form but different zero-points (i.e. be offset but parallel). This is clearly not the case for most galaxies, however, and the profiles of most galaxies with a B/PS bulge differ significantly (e.g. Fig. 1). Although we have amalgamated the bulge and disc by considering a single scaleheight, the functional difference between the two profiles is greatest in the flat intermediate regions, which are clearly disc material dominated. Our profiles thus clearly show that the radial scaleheight variations are real and that they occur in the discs, in direct contradiction to the common wisdom that disc scaleheights are constant (e.g. van der Kruit & Searle 1981). Athanassoula et al. (2005) show that the variations are as expected from barred N-body models.

Galaxy bulges are usually defined as either 1) the steep central component of the surface brightness profile or 2) the thick galactic component. Those definitions are normally used interchangeably, but many results show this to be grossly oversimplified (e.g. Kormendy & Kennicutt 2004). Our data clearly show that the central peak is often contained *within* the thick central component, while the shallow intermediate region always extends *beyond* the thick component (e.g. Fig. 1). Those facts are unaccounted for in classic bulge formation scenarios, but they are a natural consequence of the bar viewing angle and the fact that only part of the bar is actually thick in bar-buckling models (see Athanassoula 2005 for more on this last point).

Comparison of the major-axis and vertically-summed profiles also reveals that the central peak is more pronounced along the major-axis, so that most of the high z material belongs to the shallow intermediate region rather than the central peak. The latter thus seems to be a thin concentrated disc, while the former appears to be thick. This is again counter to the classic bulge + disc model, but fits with the nomenclature proposed by Athanassoula (2005). The bar leads to the formation of a concentrated disc (a disc-like bulge), presumably through (bar-driven) gaseous inflow and star formation, but this disc is thin, largely decoupled from the bar, and addresses only the first bulge definition. The bar itself is thick over most but not all its length (a B/PS bulge), with a shallow profile, and addresses the second bulge definition. Like the classic models, our model comprises a number of distinct building blocks, but those are very different and tightly intertwined dynamically, emerging from the rapid radial variation of the scaleheight of the disc material, due to the weak but relentless action of bar-related resonances.

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