Formation of Boxy/Peanut-Shaped Bulges in Spiral Galaxies: Accretion or Bar-Buckling Instability?

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Abstract: We present results of an observational program aimed at identifying the formation mechanism of boxy/peanut-shaped bulges in spiral galaxies. We concentrate on the accretion and bar-buckling instability theories: although satellite accretion is an attractive way to form boxy/peanut bulges, we show that the bar-buckling instability is the more likely cause of the bulges' shape in the majority of cases. Nevertheless, some objects do not harbour a bar and others are clearly interacting, so the accretion mechanism is relevant in some systems and the possibility of hybrid scenarios must be raised. The related X-shaped galaxies are also discussed.

Introduction

Boxy/peanut-shaped bulge galaxies constitute an important class of spiral galaxies: they are numerous (20-30% of all spirals) and display interesting dynamics and structure (cylindrical rotation and large deviations from a spheroidal shape).

In the 1980's, it was widely believed that accretion was the dominant formation mechanism of boxy/peanut galaxies. The slow accretion of material from satellite galaxies on to a host galaxy can naturally give rise to a boxy/peanut bulge shape.

However, since the early 1990's, the emphasis has changed. The favoured way of explaining boxy/peanut galaxies is now through the bar-buckling instability. Thin bars do not form or are unstable to buckling modes, and settle with an increased thickness, looking boxy when the bar is seen end-on, and peanut-shaped when the bar is seen side-on.

The present project aims to determine the dynamical state of a sample of 30 edge-on spiral galaxies. About 3/4 of these have boxy/peanut-shaped bulges, and the rest have various morphologies; almost half have possible companions. The primary goal is to identify which of the formation mechanisms proposed for boxy/peanut galaxies is dominant.

This project is part of a larger program on the vertical structure of (barred) spiral galaxies, also including near-infrared and optical imaging and some HI line-imaging: see Bureau & Freeman (1997).

Accretion Mechanism

Binney & Petrou (1985) and Rowley (1988) constructed distribution functions that generate axisymmetric boxy/peanut-shaped bulges. Both argued that the best way to form the required distribution functions is through the slow accretion of material.

If the (oblique) orbit of a small satellite galaxy decays toward a host galaxy with a decay time-scale much longer than the orbital time, the material shed by the satellite can populate phase space appropriately and settle in a boxy/peanut bulge shape.

Whitmore & Bell (1988) argued that **a rich variety of bulge shape (from X to box-shape) arises when a companion galaxy decays toward a flattened potential because the oblique disk spreads out quickly into a precession cone, forming an X-shape structure (in projection) superposed on the bulge.** The simulations of Hernquist & Quinn (1988) also show that orbits of accreted stars can appear X-shaped.

Recent or ongoing accretion events should leave obvious traces in the kinematics of the main galaxy and should be detectable as irregularities in the rotation curve (see Figure 1). Such kinematical observations are presented here and aim partly to evaluate the importance of accretion in forming boxy/peanut bulges. Unfortunately, it is very hard based on the kinematics alone to discriminate between a "primordial" axisymmetric boxy/peanut-shaped bulge and one formed through accretion but which has already settled into an axisymmetric equilibrium state.

Bar-Buckling Instability

Combes et al. (1990) and Raha et al. (1991) followed up on the original work of Combes & Sanders (1981) and studied how boxy/peanut-shaped bulges can form through the buckling of a (thin) bar in 3D N-body simulations.

Buckling modes develop in a disk when the vertical velocity dispersion is less than about a third of the velocity dispersion in the plane (Toomre 1966). Because bar formation makes the orbits in a disk more eccentric and aligns their principal axes without greatly affecting the motion perpendicular to the plane, **thin bars are unstable against buckling; they thicken, and settle with an increased velocity dispersion and thickness, appearing boxy or peanut-shaped in projection, depending on the viewing angle. Similarly, thin bars might not form at all.**

Kuijken & Merrifield (1995) and Merrifield (1996) showed that **it is possible to identify bars in edge-on systems through the particular signature they leave in their position-velocity diagram (PVD; see Figure 2).** Because the gas follows non-intersecting orbits, and there are no such orbits around corotation in a barred galaxy, a characteristic gap will appear in the projected gaseous PVD (compared to that of an axisymmetric galaxy).

The main aim of our observational program is to use this effect to detect bars in edge-on galaxies, particularly boxy/peanut systems, in order to study the importance of the bar-buckling instability in galaxies, and to yield a useful sample for follow-up studies of edge-on bars.

Results & Discussion

The table presents a quick summary of our observational results. The sample galaxies are grouped according to their bulge morphology, their emission lines spectrum structure is described, and the most probable formation mechanism for the bulge is identified. The absorption lines kinematics has not been analysed yet so these constitute preliminary results.

From the regularity of their rotation curves, **very few boxy/peanut bulges seem to originate from accretion of material,** despite the fact that many systems have a possible companion(s). **Those galaxies also tend to have the most extreme bulge morphologies.**

This result is consistent with the best examples of boxy/peanut bulges being found in small groups, while as a class they are not preferentially found in clusters (Shaw 1987), and also with the observation that only a small range of initial conditions can lead to boxy/peanut bulges through accretion.

Many boxy/peanut galaxies display the signature of a bar. In addition, most systems with regular spectrum (i.e. normal rotation curve) outside the control sample are dusty, opening the possibility that the bar signature is simply hidden from view (e.g IC 2531). **Those galaxies also tend to have regular bulge morphologies, resembling those seen in N-body simulations.**

This result is in agreement with the fact that the fraction of boxy/peanut bulge systems among edge-on spirals is similar to the fraction of strongly barred systems among face-on spirals (Shaw 1987, de Souza & dos Anjos 1987, Jarvis 1986). It also has the advantage of providing a way for isolated galaxies to develop a boxy/peanut-shaped bulge.

In short, our results point to a picture where the majority of boxy/peanut-shaped bulges are due to the presence of a thick bar seen edge-on, and only a few (usually extreme) cases are formed through accretion.

Because some barred systems also have companions, the possibility remains of hybrid scenarios between the two formation mechanisms, where a bar in a stable disk is excited by the presence of a satellite(s) and buckles due to the bar-buckling instability (e.g Mihos et al. 1995).

Furthermore, **none of the galaxies in the control sample displays obvious evidence of either accretion or the presence of a bar.** The bulges of these systems are probably typical axisymmetric spheroids.

This result indicates that while a boxy/peanut bulge does not necessarily imply the presence of a bar (because of the few accretion cases), **spheroidal bulges do appear to be axisymmetric systems.**

Acknowledgements

We wish to thank A. Kalnajs, L. Sparke, Y.-I. Byun, A. Bosma, & T. de Zeeuw for fruitful discussions. M. Bureau acknowledges the support of an Australian DEETYA Overseas Postgraduate Research Scholarship, a Canadian NSERC Postgraduate Scholarship, and an Astronomical Society of Australia travel grant to attend this meeting.

The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope.

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Figures

Figure 1 & 2 show data for a subset of our sample. The goal is to illustrate the spectral features used to identify either ongoing/recent accretion (Figure 1) or the presence of a bar (Figure 2) in the galaxies' disks. In each case, both boxy, peanut, and X-shaped bulges are displayed to illustrate the full range of bulge morphology considered.

Each panel is composed of the emission line spectrum (position-velocity diagram, PVD) of the galaxy at the bottom left, an image of the galaxy at the same scale on top, and a 15' field centered on the galaxy on the right. Features in the PVD can be related to features in the galaxy using the images on the left, and the "wide-field" image is used to identify possible companions.

Irregular PVDs are characteristic of galaxies interacting with a companion(s), while double-peaked symmetric PVDs are the signature of a bar.

Galaxy	**Spectrum**	**Notes**	**Formation**
X-shape:			
ESO 151-G04	Bar signature.		Bar buckling.
ESO 597-G36	Irregular.	Companions. Dusty.	Accretion.
Butterfly:			
NGC 2788a	Regular.	Companion? Very dusty.	?
ESO 443-G42	Regular.	Companion? Very dusty.	?
IC 4767	Confined emission.	Companions.	?
NGC 6771	Bar signature.	Companions.	Bar buckling.
ESO 185-G53	No emission.	Companions.	?
Peanut:			
NGC 128	Confined emission.	Counter-rotating. Companions.	Accretion.
IC 2531	Regular.	Bar signature in HI. Very dusty.	Bar buckling.
NGC 4388	Regular.	Dusty.	?
NGC 4469	Confined emission.	Companions?	?
PGC 44931	Bar signature.		Bar buckling.
NGC 5746	Bar signature.		Bar buckling.
NGC 6722	Bar signature.		Bar buckling.
IC 4937	Bar signature.	Companions?	Bar buckling.

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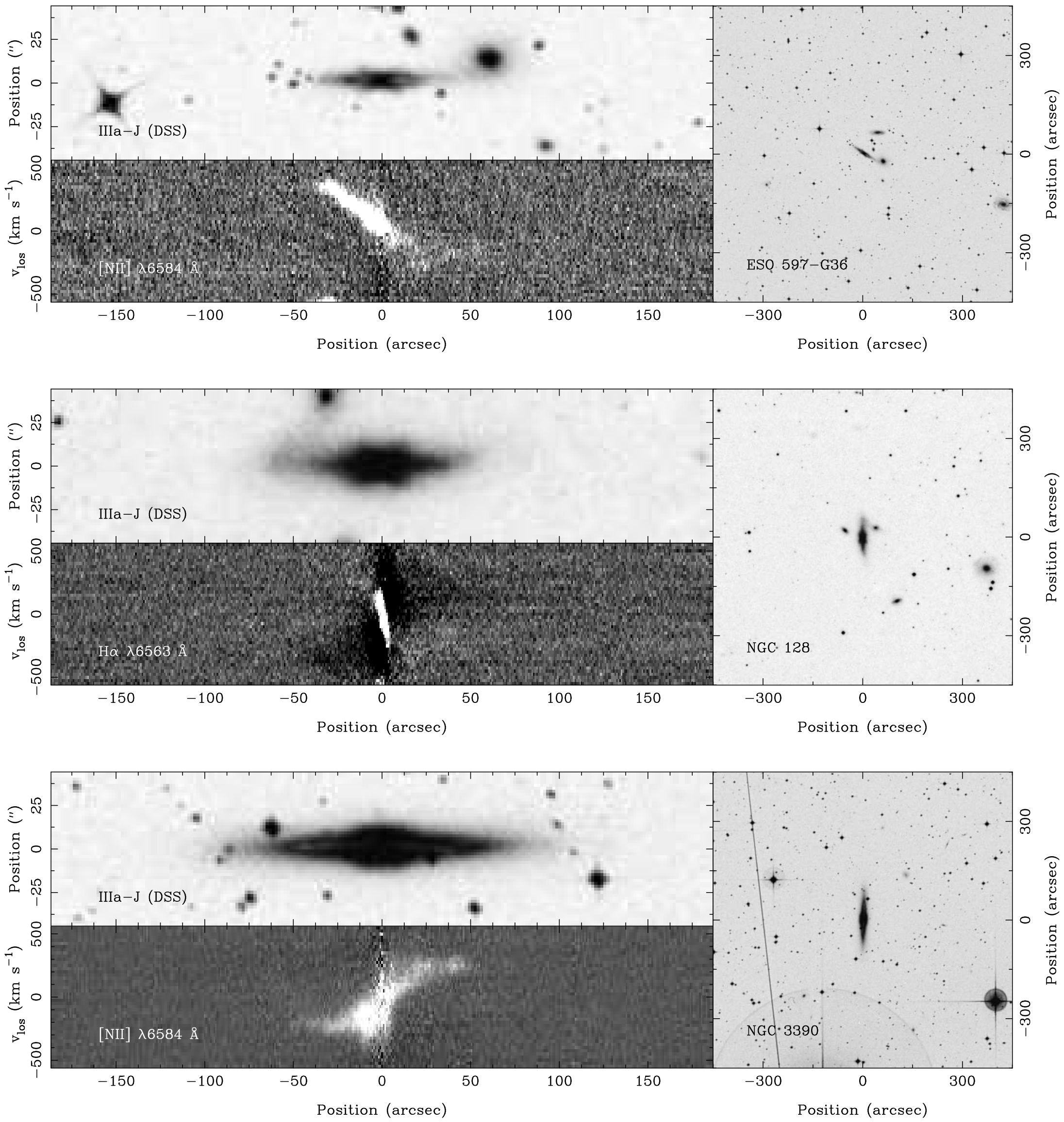
Galaxy	**Spectrum**	**Notes**	**Formation**
Boxy:			
NGC 1381	No emission.		?
NGC 1596	No emission.	Companion.	?
NGC 1886	Bar signature.		Bar buckling.
NGC 2310	No emission.		?
ESO 311-G12	Confined emission.		?
NGC 3203	No emission.	Companions.	?
NGC 3390	Peculiar.	Companion?	Accretion.
NGC 4710	Bar signature.		Bar buckling.
IC 5096	Bar signature.		Bar buckling.
- - - - - - - - - -	- - - - - - - *Control*	*Sample* - - - - - - - -	- - - - - - - - - -
Ellipsoidal:			
NGC 3957	Regular.		?
NGC 4703	Regular.	Dusty.	?
NGC 5084	Peculiar.		?
Exponential:			
NGC 1032	Regular.	Dusty.	?
NGC 7123	Regular.	Very dusty.	?
Late-Type:			
IC 5176	Regular.	Companion?	?
ESO 240-G11	Regular.		?

Figure 1.
Accretion Mechanism



X shape

Peanut shape

Boxy shape

Figure 2.
Buckling Instability

X shape

Peanut shape

Boxy shape