Bars and boxy/peanut-shaped bulges: an observational point of view

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Prompted by work on the buckling instability in barred spiral galaxies, much effort has been devoted lately to the study of boxy/peanut-shaped (B/PS) bulges. Here, we present new bar diagnostics for edge-on spiral galaxies based on periodic orbits calculations and hydrodynamical simulations. Both approaches provide reliable ways to identify bars and their orientations in edge-on systems. We also present the results of an observational search for bars in a large sample of edge-on spirals with and without B/PS bulges. We show that most B/PS bulges are due to the presence of a thick bar viewed edge-on while only a few may be due to accretion. This strongly supports the bar-buckling mechanism for the formation of B/PS bulges.

1. Introduction

Boxy/peanut-shaped (B/PS) bulges have, as their name indicates, excess light above the plane. They are thus easily identified in edge-on systems and display many interesting properties: their luminosity excess, an extreme three-dimensional structure, probable cylindrical rotation, etc. However, the main importance of B/PS bulges resides in their incidence: at least 20-30% of all spiral galaxies possess a B/PS bulge. They are thus essential to our understanding of bulge formation and evolution.

Early theories on the formation of B/PS bulges were centered around accretion scenarios, where one or many satellites galaxies are accreted onto a preexisting bulge, and which lead to axisymmetric structures (e.g. Binney & Petrou 1985). However, such scenarios are restrictive, and it seems that the only viable path is the accretion of a small number of moderate-sized satellites. Thus, accretion probably plays only a minor role in the formation of B/PS bulges. A more attractive mechanism is the buckling of a bar, due to vertical instabilities. This process can form B/PS bulges even in isolated galaxies, and accounts easily for the fact that the fraction of B/PS bulges is similar to that of (strongly) barred spirals. Soon after a bar is formed, it buckles and settles with an increased thickness, appearing boxy or peanut-shaped depending on the viewing angle (e.g. Combes *et al.* 1990). Hybrid scenarios, where a bar is excited by an interaction and then buckles, have also been suggested.

To test as directly as possible the bar-buckling hypothesis, we have developed reliable bar diagnostics for edge-on spirals (Bureau & Athanassoula 1999; Athanassoula & Bureau 1999), and have searched for bars in a sample of edge-on galaxies with and without B/PS bulges (Bureau & Freeman 1999). This way, we can probe the exact relationship between bars and B/PS bulges.

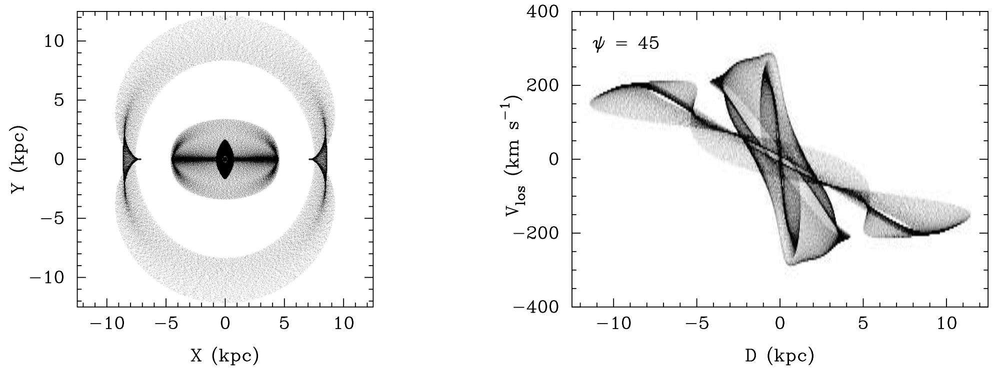

FIGURE 1. Surface density distribution (*left*) and projected PVD (*right*) of model 001, when considering the x_1, x_2, and outer 2:1 families of periodic orbits. In the left plot, the bar is horizontal, has a length of 5 kpc, and is viewed at an angle of 45° for the PVD.

2. Bar diagnostics in edge-on spiral galaxies: the periodic orbits approach

There is no reliable photometric way to identify a bar in an edge-on spiral galaxy. However, Kuijken & Merrifield (1995) showed that an edge-on barred disk produces characteristic double-peaked line-of-sight velocity distributions which would not occur in an axisymmetric disk. Following their work, we also developed bar diagnostics based on the position-velocity diagrams (PVDs) of edge-on disks, which show the projected density of material as a function of line-of-sight velocity and projected position. The mass model we adopted has a Ferrers bar, two axisymmetric components yielding a flat rotation curve, and four free parameters. All our models are two-dimensional.

We first used the families of periodic orbits in our mass model as building blocks to model real galaxies (Bureau & Athanassoula 1999). Such an approach provides essential insight into the (projected) kinematics of spirals. We showed that the global appearance of a PVD can be used as a reliable tool to identify bars in edge-on disks. Specifically, the presence of gaps between the signatures of the various periodic orbit families follows directly from the non-homogeneous distribution of orbits in a barred galaxy. The two so-called forbidden quadrants of the PVDs are also populated because of the elongated shape of the orbits. Figure 1 shows the surface density and projected PVD of a typical model. The bar is viewed at an angle of 45° from the major axis and only the major families of periodic orbits are considered. The signatures of the x_1 (parallel to the bar) and x_2 (perpendicular to the bar) orbits are particularly important to identify the bar and constrain the viewing angle. Because of streaming, the parallelogram-shaped signature of the x_1 orbits reaches very high radial velocities when the bar is seen end-on and only relatively low velocities when it is seen side-on. The opposite is true for the x_2 orbits.

3. Bar diagnostics in edge-on spiral galaxies: hydrodynamical simulations

We also developed bar diagnostics using hydrodynamical simulations, targeting specifically the gaseous component of spiral galaxies (Athanassoula & Bureau 1999). The simulations are time-dependent and the gas is treated as ideal, isothermal, and non-viscous. We used the same mass model as above, without self-gravity, and modeled star formation and mass loss in a simplistic way. However, the collisional nature of the gas leads to better bar diagnostics than the periodic orbits approach.

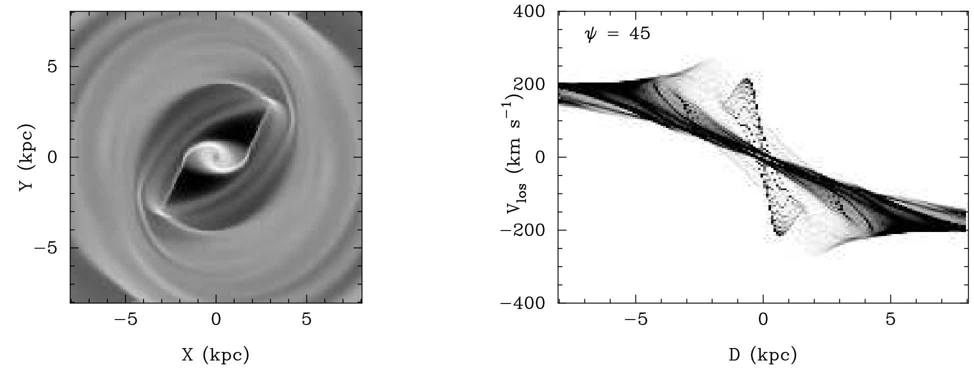

FIGURE 2. Surface density distribution (*left*) and projected PVD (*right*) of model 001, for the hydrodynamical simulations. In the left plot, the bar is now oriented diagonally and high densities are in white.

The main feature of the PVDs is a gap, present at all viewing angles, between the signature of the nuclear spiral (associated with x_2 orbits) and that of the outer parts of the disks. There is very little gas in x_1-like flows. This gap unmistakably reveals the presence of a bar in an edge-on disk. It occurs because the large scale shocks which develop in bars drive an inflow of gas toward the centers, depleting the outer bar regions. If a galaxy has no inner Lindblad resonance (ILR; or, equivalently, has no x_2 orbits), there is no nuclear spiral and the entire bar region is depleted. Then, the use of stellar kinematics is probably preferable to identify a bar. We will develop such diagnostics in a future paper. Figure 2 shows the gas density distribution and PVD for the same model as above, which has ILRs. Although not shown, the PVDs again vary significantly with the viewing angle, the signature of the nuclear spiral reaching its highest velocities when the bar is seen close to side-on. We also ran simulations covering a large fraction of the parameter space likely to be occupied by real galaxies. The PVDs can then be used to somewhat constrain the mass distribution and bar properties of observed systems.

4. The nature of boxy/peanut-shape bulges

The PVDs produced are directly comparable to kinematic observations of edge-on spiral galaxies. In the hope of understanding the formation mechanism of B/PS bulges, we searched for bars in a sample of 30 edge-on spirals with and without B/PS bulges, using emission line long-slit spectroscopy (Bureau & Freeman 1999). The objects were selected from existing catalogs and 2/3 have probable companions. Of the 24 galaxies with a B/PS bulge, 17 have extended emission lines and constitutes our main sample. The remaining 6 galaxies all have extended emission and form a control sample.

In the main sample, 14 galaxies display a clear bar signature in their PVD, and only 3 may be axisymmetric or have suffered interactions. None of the galaxies in the control sample shows evidence for a bar. This means that most B/PS bulges are due to the presence of a thick bar viewed edge-on and only a few may be due to the accretion of external material. In addition, spheroidal bulges do appear axisymmetric. Thus, it seems that most B/PS bulges are edge-on bars and that most bars are B/PS when viewed edge-on. However, the strength of this converse is limited by the small size of the control sample. To illustrate our data, we show the PVD of two galaxies in the main sample in figure 3. Our association of bars and B/PS bulges is supported by the anomalous emission line ratios observed in many objects. These galaxies display large

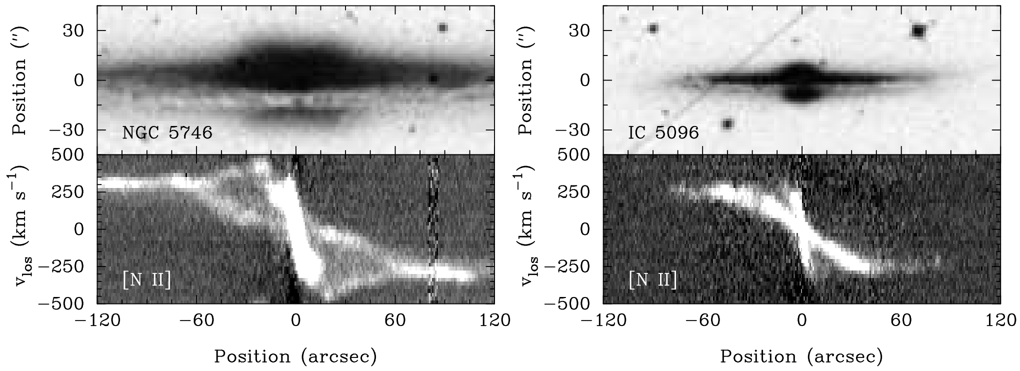

FIGURE 3. Image and ionised gas PVD (on the same scale and along the major axis) of two B/PS galaxies. The bar signature in the bulge region is obvious in both cases.

Hα/[N II] ratios, often associated with shocks, and these ratios correlate with kinematical structures in the disks. Constraining the viewing angle to the galaxies with our models, the observations also appear to confirm the general prediction of N-body simulations, that bars are peanut-shaped when seen side-on and boxy-shaped when seen end-on.

Our results are consistent with the current knowledge on the bulge of the Milky Way and strongly support the bar-buckling mechanism for the formation of B/PS bulges. However, we do not test directly for buckling, and other bar-thickening mechanisms and hybrid scenarios can not be excluded. Nevertheless, it is clear that the influence of bars on the formation and evolution of bulges is primordial.

5. On-going studies

The bar diagnostics we have developed open up for the first time the possibility of studying the vertical structure of bars observationally. To this end, we have obtained K-band images of all the sample galaxies. We have also obtained absorption line spectroscopic data to study the stellar kinematics, and a more in-depth investigation of line ratios will give us a better understanding of the large scale effects of bars in disks.

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