The Vertical Structure of Bars

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Abstract: We introduce new diagnostics to identify bars in edge-on spiral galaxies, based on periodic orbits calculations and hydrodynamical simulations. We also present a search for bars in a large sample of edge-on spirals, most of which have a boxy or peanut-shaped (B/PS) bulge. Our data clearly shows that B/PS bulges are systematically barred, while normal bulges appear axisymmetric. This strongly supports the view that thin bars are vertically unstable and that real bars are thick and appear B/PS when viewed edge-on.

1 Introduction

Very little is known about the three-dimensional structure of bars, and what we do know comes mainly from N-body simulations. The ability to identify barred systems in edge-on spiral galaxies is a prerequisite to study observationally the vertical structure of bars. Because morphological indications are unreliable, **we have developed bar diagnostics relying on the particular kinematics of barred disks, which is easily differentiated from that of axisymmetric systems**. The periodic orbits of barred spirals, and the way the ISM populates these, lead to simple diagnostics based on the position-velocity diagrams (PVDs) of edge-on disks taken along the major axis. We discuss those diagnostics in Sections 2 and 3.

The first step to study the vertical structure of bars is to construct a large sample of edge-on barred galaxies, which can then be studied more closely with follow-up observations, preferentially in the near-infrared to minimize the effects of dust. N-body simulations suggest that bars are boxy/peanut-shaped (B/PS) when viewed edge-on, due to the buckling instability (e.g. Combes & Sanders 1981), but accretion of external material can also lead to axisymmetric B/PS systems (Binney & Petrou 1985). **We have thus carried out a search for bars in a large sample of edge-on spirals, targeting especially objects with a B/PS bulge.** We discuss our results in Section 4. Hybrid scenarios, combining buckling and accretion, may also be important. However, we associate those with buckling, since accretion is then only a way to start the bar formation process, and is largely unrelated to the bar thickening.

2 Periodic Orbits Calculations

Kuijken & Merrifield (1995) showed that an edge-on barred disk has characteristic double-peaked line-of-sight velocity distributions which would not occur in an axisymmetric system. Here, we use families of periodic orbits as building blocks to model real galaxies. Our mass model is two-dimensional, has a Ferrers bar, two axisymmetric components yielding a flat rotation curve, and a total of four free parameters (see Athanassoula 1992a). The surface density and PVDs of the major periodic orbit families of model 001, which has an inner Lindblad resonance (ILR), are shown in Figure 1. The PVDs show the projected density of material as a function of line-of-sight velocity and projected position along the major axis for various viewing angles.

Figure 1 illustrates that **the global appearance of a PVD is a reliable tool to identify bars in edge-on disks. The gaps between the signatures of the various periodic orbit families are a direct consequence of the non-homogeneous distribution of orbits in barred disks.** As expected, because the orbits are elongated, the forbidden quadrants are populated. The x_1 and x_2 orbits (respectively parallel and perpendicular to the bar) are the most important families for identifying a bar and its orientation with respect to the line-of-sight. The x_1 orbits reach very high velocities when the bar is seen end-on and only low velocities when it is seen side-on. The opposite is true for the x_2 orbits.

The models shown here provide only a first order view of the projected stellar kinematics of edge-on barred disks, but we are currently developing more realistic stellar diagnostics using N-body simulations. These will be directly comparable with observations.

3 Hydrodynamical Simulations

Periodic orbits provide essential insight into the projected kinematics of barred galaxies. However, to create diagnostics better adapted to the gaseous component of spirals, one must properly take into account the collisional nature of gas. We present here hydrodynamical simulations which use the same mass model as the orbital calculations. The simulations are two-dimensional, time-dependent, and the gas is treated as ideal, isothermal, and non-viscous. There is no self-gravity and star formation and mass loss are treated in a simple way (see Athanassoula 1992b). Figure 2 shows the simulated gas surface density and PVDs for model 001.

The main feature of the PVDs is the gap, present at all viewing angles, between the signature of the nuclear spiral (associated with the x_2 orbits) and that of the outer parts of the disk. Such a gap in a PVD unmistakably reveals the presence of a bar. It occurs because large scale shocks in bars drive the gas toward the center and deplete the regions of the disks occupied by an x_1-like flow. The ratio of the maximum velocity reached by the nuclear spiral to that reached by the outer disk is particularly useful to constrain the viewing angle to the bar. The large fraction of parameter space covered by our models also allows to constrain the mass distribution and bar properties of edge-on galaxies using PVDs.

If a galaxy has no ILR (or, equivalently, has no x_2 orbits or nuclear spiral), the entire bar region is depleted and the above diagnostics can not be applied. One must then rely on the stellar kinematics to identify a bar.

4 Observations

With the goal of studying the vertical structure of bars, we have used the diagnostics developed to search for bars in a large sample of edge-on spirals with and without B/PS bulges and in a variety of environments. Of the 30 galaxies for which we obtained optical long-slit spectroscopy, 17 galaxies with a B/PS bulge and 6 galaxies without a B/PS bulge showed extended emission lines. These constitute our main and control sample, respectively. The remaining galaxies, for which stellar kinematics must be used, will be studied when N-body diagnostics are available. To illustrate the types of PVDs encountered, we present some of our observations in Figure 3.

The results of our study are easy to summarize: 14 of the 17 galaxies in the main sample display a clear bar signature, and only 3 may be axisymmetric or have suffered recent interactions. None of the galaxies in the control sample shows evidence for a bar. This indicates that **B/PS bulges are closely associated with edge-on bars, accretion plays at most a minor role in their formation, and ellipsoidal bulges are indeed axisymmetric. It also suggests that most B/PS bulges are (thick) bars viewed edge-on and that most bars are B/PS when viewed edge-on.** Clearly, however, observations of a larger number of non-B/PS bulges are needed to make this converse stronger. Our results are also consistent with the view that boxy bulges are associated with end-on bars while peanut bulges arise from side-on bars.

The observations presented here offer a first and much needed observational glimpse at the vertical structure of bars. However, much work remains to be done to refine this picture. To this end, we have already acquired BVI and K-band images of the sample galaxies, and will report on these in the near future.

Notes

The periodic orbits calculations, hydrodynamical simulations, and observational results will appear in a series of paper in ApJ and AJ during the Summer and Autumn. Preprints are available on astro-ph (9903061, 9904206, 9904015) and at <http://www.strw.leidenuniv.nl/~bureau/pub_list.html>.

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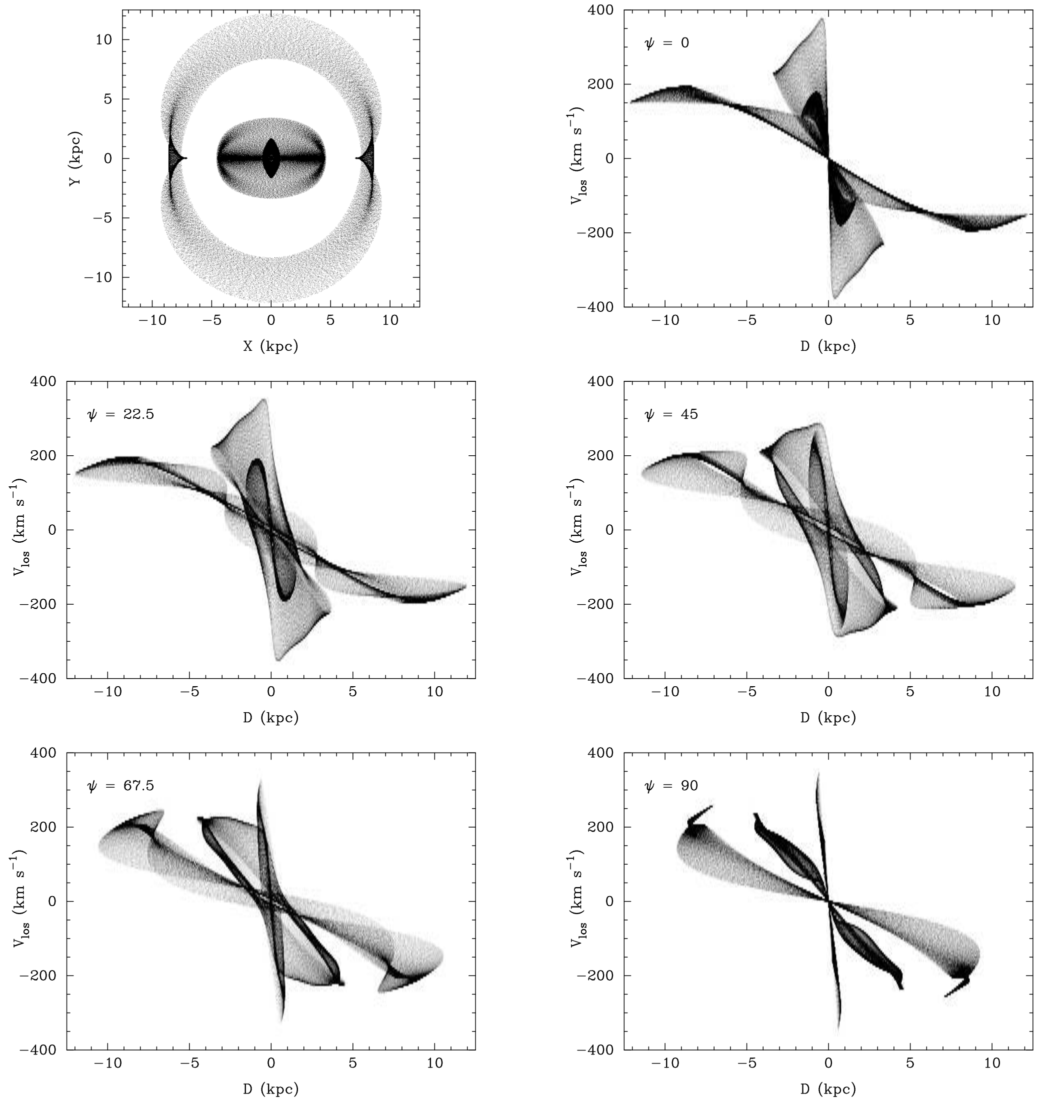
Comments:

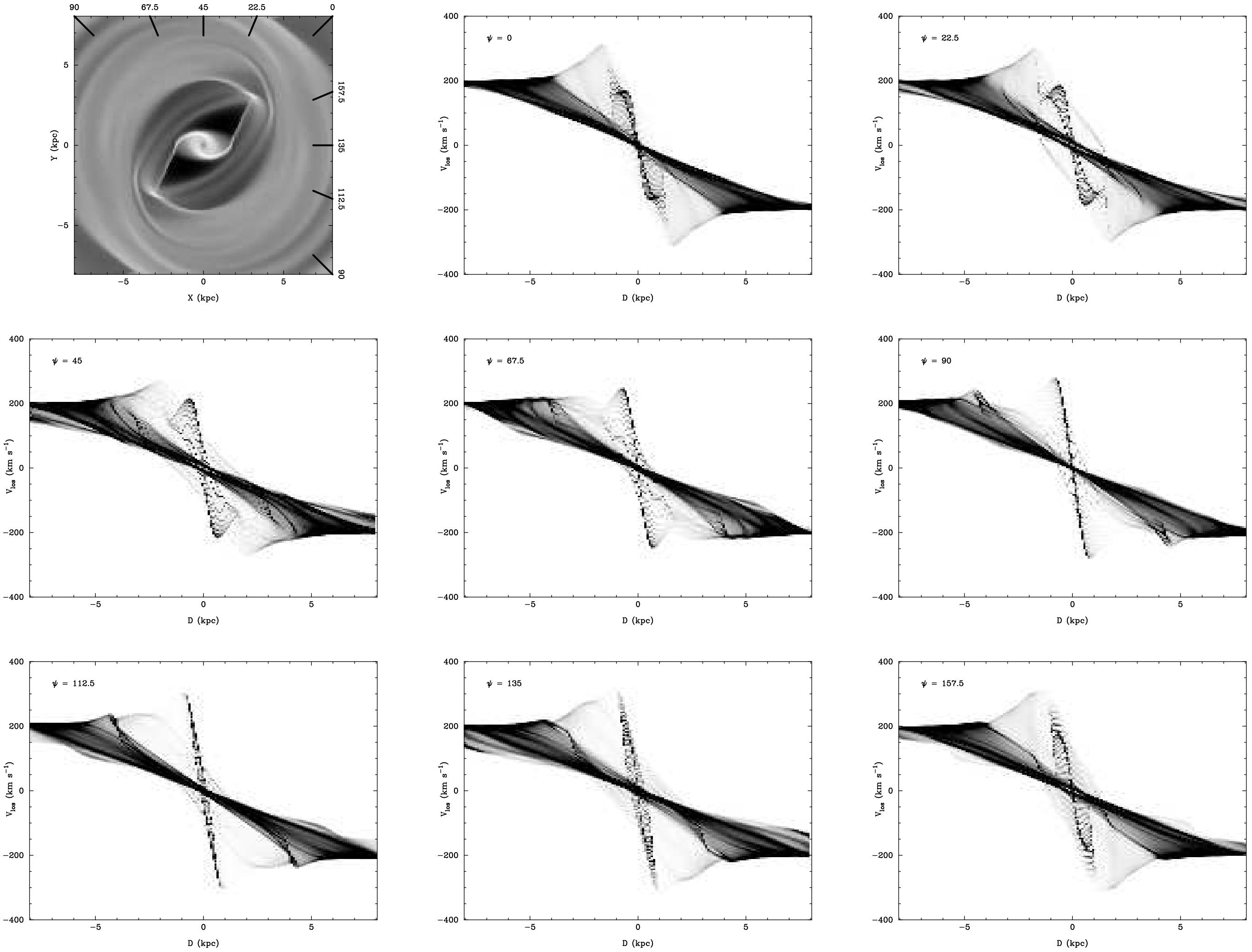
Figure 1: Surface density (*top-left*) and PVDs of model 001 when considering the x_1, x_2, and outer 2:1 families of periodic orbits only. In the top-left plot, the bar is horizontal and has a length of 5 kpc. The viewing angle ψ is defined as 0° parallel to the bar and increases counterclockwise.

Figure 2: Surface density distribution (*top-left*) and PVDs of model 001 from the hydrodynamical simulations. The scale is logarithmic for the surface densities only, because of high dynamic range. The bar is oriented diagonally in the top-left plot.

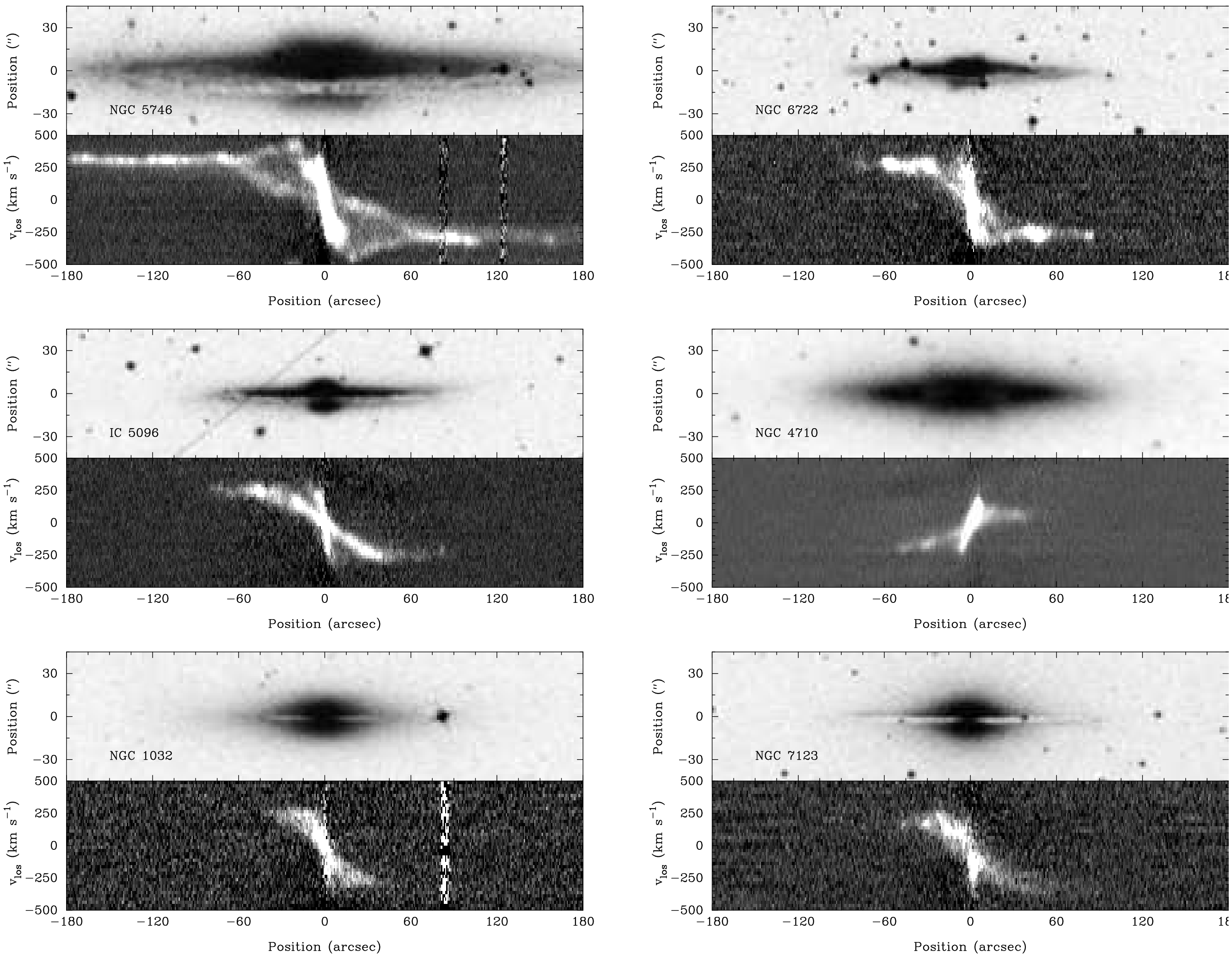
Figure 3: Images (DSS) and ionized gas PVDs ([N II]) of 6 sample galaxies. The *first* and *second rows* show galaxies with peanut and boxy bulges, respectively. All display a clear bar signature in their PVD. The *third row* shows galaxies with ellipsoidal bulges. The PVDs indicate respectively an axisymmetric and a disturbed disk.



Y (kpc)
X (kpc)
ψ = 0
ψ = 22.5
ψ = 45
ψ = 67.5
ψ = 90
V_{los} (km s^{-1})
D (kpc)



90
67.5
45
22.5
0
157.5
135
112.5
90
Y (kpc)
X (kpc)
ψ = 0
ψ = 22.5
ψ = 45
ψ = 67.5
ψ = 90
ψ = 112.5
ψ = 135
ψ = 157.5
V_los (km s^-1)
D (kpc)


NGC 5746
NGC 6722
IC 5096
NGC 4710
NGC 1032
NGC 7123
Position (″)
v_los (km s^−1)
Position (arcsec)
30
0
−30
500
250
0
−250
−500
−180
−120
−60
0
60
120
180