

Letter to the Editor

Hidden bars and boxy bulges

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Abstract. It has been suggested that the boxy and peanut-shaped bulges found in some edge-on galaxies are galactic bars viewed from the side. We investigate this hypothesis by presenting emission-line spectra for a sample of 10 edge-on galaxies that display a variety of bulge morphologies. To avoid potential biases in the classification of this morphology, we use an objective measure of bulge shape. Generally, bulges classified as more boxy show the more complicated kinematics characteristic of edge-on bars, confirming the intimate relation between the two phenomena.

Key words: galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure

1. Introduction

For some considerable time, N-Body simulations have predicted the existence of a vertical instability in galactic bars (Combes & Sanders 1981, Combes et al. 1990, Raha et al. 1991). These simulations show that a bar forming in a flat disk will not remain thin, but will quickly buckle and form a thickened structure perpendicular to the plane of the disk. Viewed edge-on, such fat bars have a characteristic shape with very boxy isophotes. In the most extreme cases, the structure appears double-lobed, like a peanut in its shell. These simulations are intriguing because observations of real edge-on galaxies reveal that a significant fraction have central bulges with boxy or peanut-shaped isophotes (Jarvis 1986, Shaw 1987, de Souza & dos Anjos 1987). It is therefore tempting to associate such bulge morphologies with edge-on bars, and even draw more general conclusions regarding the formation of all bulges.

Unfortunately, establishing the link between bars and boxy bulges observationally has proved difficult. Bars are recognizable only in fairly face-on galaxies, while the vertical structure

of a bulge can only be deduced from an edge-on view. Thus, it has proved impossible to connect the two phenomena unequivocally using photometric data.

A few years ago, we suggested that bars could be detected in edge-on galaxies from their kinematic signature (Kuijken & Merrifield 1995). The orbits followed by material in a barred potential will be non-circular, and the arrangement of the orbits changes abruptly near resonances. As a consequence of this complexity, the observable line-of-sight velocities of material as a function of position in an edge-on barred galaxy will also display complex structure, with multiple components and gaps associated with the resonances. The existence of this complexity, which we originally investigated using simple perturbation theory applied to closed orbits, has subsequently been confirmed by full hydrodynamical gas simulations (Athanasoula & Bureau 1999).

In a pilot spectral study, we found such kinematic structure in both the stellar and gaseous components of two edge-on disk galaxies (Kuijken & Merrifield 1995). Since these galaxies were selected because they contained peanut-shaped bulges, this discovery provided some evidence that bars and boxy bulges are the same phenomenon viewed from different directions. However, the sample size was very small, and lacked comparison data from galaxies without boxy bulges.

We have therefore now carried out a larger spectral survey of edge-on galaxies. The sample was taken from the largest early-type disk galaxies observable from the northern hemisphere in the RC3 catalog (de Vaucouleurs et al. 1991), from which we selected a subset of 10 galaxies designed to span a complete range in bulge morphology, from elliptical to peanut-shaped. Sect. 2 describes how the shapes of these bulges have been quantified, while Sect. 3 presents the spectral data. The results and their implications are discussed in Sect. 4.

2. Bulge shapes

Previous studies of bulge shapes (e.g. Jarvis 1986, Shaw 1987, de Souza & dos Anjos 1987) have been based on the visual impression of galaxies in sky survey plates. Unfortunately, this subjective approach cannot be used reliably when comparing the bulge shapes to other properties of galaxies such as their

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kinematics. If, for example, we were to detect complex kinematics in a galaxy, there is a significant risk that we would then reinforce our initial prejudice by convincing ourselves that there were signs of boxiness in the galaxy's isophotes. What we require, therefore, is some more objective approach.

In the case of elliptical galaxies, shapes are relatively easy to classify by measuring the minor departures of the isophotes from ellipses (e.g. Bender, Döbereiner & Möllenhoff 1988). However, the analysis of an edge-on disk galaxy is less straightforward, as the contribution to the total light from the disk, as well as dust absorption in the disk plane somewhat confuse the bulge isophotal shapes. Nevertheless, after some experiments we have found that it is possible to obtain robust measures of the bulge isophotes using the techniques developed for elliptical galaxies.

Images of most of our sample galaxies' bulges were obtained in the I band at the William Herschel Telescope along with the spectral data described below. Where this was not possible, we have searched the La Palma archive, or failing this, used the Digitized Sky Survey (DSS). We have measured the bulge isophotes with the ELLIPSE task in the STSDAS analysis package of IRAF (Jedrzejewski 1987). We masked out a wedge-shaped region of each image within 12 degrees of the disk major axis to minimize the disk influence, and, in order to minimize the effects of extinction by the disk, only fitted on the side of the galaxy where the disk projects behind the bulge. The masking process leaves less than half of the isophote available for fitting, but by fixing the centroid and position angle of the isophotes to coincide with those of the disk stable results can still be obtained.

Having measured the isophote shapes at a range of surface brightnesses, we then classified a galaxy's boxiness on the basis of the most extreme value (positive or negative) of the a_4 isophote shape parameter. Images of the half of the bulges to which the fit was applied, ordered by the value of this parameter, are presented in Fig. 1. Reassuringly, this objective ordering process arranges the galaxies in almost exactly the same sequence as one would have done by eye, but without the dangers of *a posteriori* bias that are inherent in any subjective classification.

3. Spectral data

Using the ISIS spectrograph on the William Herschel 4.2 m telescope, we obtained long-slit spectra for all the galaxies in the sample. In each case, the spectrograph slit was aligned along the major axis of the galaxy (if necessary just avoiding the dust lane). The spectra were obtained using a 1200-line grating, giving a resolution of 1 \AA (FWHM); the spectral range was centred on $H\alpha$ (6563 \AA).

We have previously found that the clearest signature of bar-induced peculiar kinematics comes from the emission lines in the spectra (Kuijken & Merrifield 1995). The strongest emission line in this spectral region is $H\alpha$ itself, but it lies on top of the $H\alpha$ absorption line associated with the stellar continuum, so its signature is somewhat confused. A clearer signal comes from the neighbouring [N II] line at 6584 \AA , which does not lie

on top of any significant absorption features. We have therefore analyzed the spectra in the vicinity of this line by first subtracting a low-order fit to the stellar continuum, then subtracting sky spectra from the ends of the slit so as to remove any night sky lines. The resulting two-dimensional spectra – intensity of the [N II] line as a function of position along the slit and wavelength – are shown in Fig. 1. The wavelength scales in this figure have been adjusted so as to present all the galaxies with similar integrated line widths, thus rendering the kinematics from different galaxies more directly comparable.

4. Discussion

From inspection of Fig. 1, it is apparent that there is, indeed, a link between bulge morphology and the complexity of the gas kinematics – generally speaking, galaxies with non-boxy bulges have a simple kinematic structure, while boxier bulges seem to be associated with complex multiple-component emission line kinematics. Bureau and Freeman (1999, 1998) reach a similar conclusion on the basis of a sample of southern galaxies. The structure apparent in the more complex emission-line kinematics shown in Fig. 1 – X-shaped two-component systems, distorted central parallelogram structures, and skewed figures-of-eight – are exactly the classes of feature that are generated by a non-axisymmetric barred potential when viewed from a variety of angles (Merrifield 1996, Bureau & Athanassoula 1999, Athanassoula & Bureau 1999). It is also notable that the radial scale over which the complex kinematics occurs is comparable in extent to the bulges of the host systems, again suggesting that the two phenomena are linked.

However, before we conclude from the association of boxy bulges with complex kinematics that these systems are bars viewed edge-on, we should consider other possible causes of complexity in the observed kinematics. One such possibility is that the gaps in the emission-line profiles result from differential extinction by dust down the line of sight. However, in axisymmetric galaxies, the line-of-sight velocity of the gas must be a smooth function of distance down the line of sight, so it is difficult to see how partial obscuration in an unbarred galaxy could result in multiple-components in the kinematics.

A second possibility is that the structure in the kinematics arises from rings of gas in the galaxy, as are seen in a number of more face-on disk systems (Buta & Combes 1996). In a two-dimensional spectrum of an edge-on galaxy, an axisymmetric ring of emission will appear as an inclined straight line. Superficially, some of the structures in the spectra in Fig. 1 conform to this pattern. However, there are several crucial differences. First, rings are edge-brightened when seen in projection, yet most of the linear features in Fig. 1 do not get brighter towards their ends. Second, axisymmetric rings project to straight lines that pass through the systemic velocity of the galaxy at its centre, whereas many of the linear features in Fig. 1 are not quite straight, and have non-zero velocities at the centres of their galaxies. Such features cannot occur in an axisymmetric potential, so we are once again forced to conclude that these galaxies are barred.

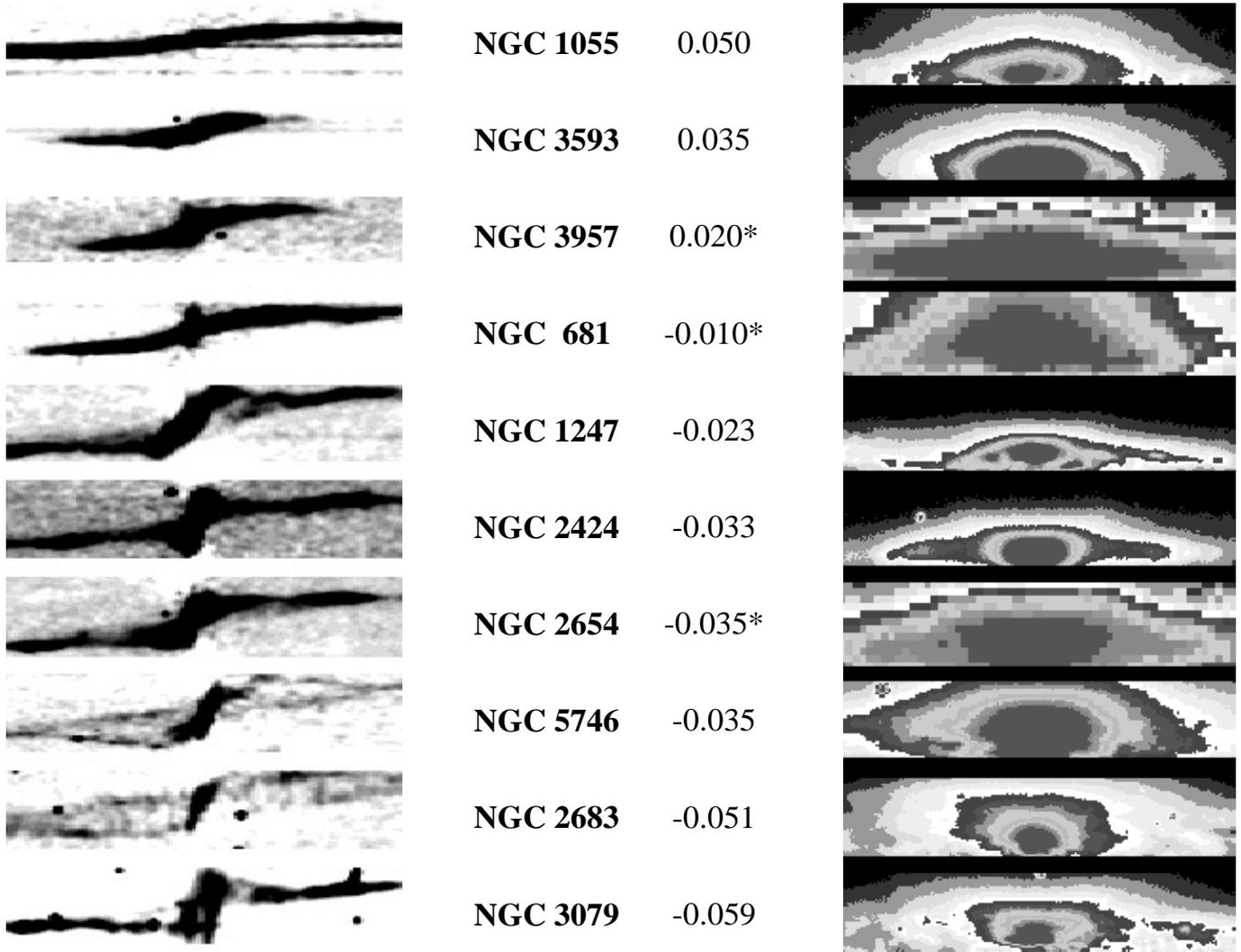


Fig. 1. Montage of the sample of 10 galaxies sorted by deviation of their bulge isophotes from disk-like (*top*) to boxy (*bottom*). The right panels show I-band CCD images of the galaxies, except for those marked with an asterisk which were taken from the Digitized Sky Survey (DSS). The left panels show the two-dimensional [N II] emission line spectra, with position along major axis as the x -axis and wavelength as the y -axis. All panels are 80 arcsecs wide. The a_4 isophote shape parameter for the least elliptical bulge isophote is listed next to the galaxy name.

A third possibility, finally, is that we are seeing variations in ionization structure of the gas, and not inhomogeneities in the distribution of the gas itself. In fact, in barred galaxies we also expect such variations, induced by the shocks; and they are indeed observed as systematic variations in $N[\text{II}]/\text{H}\alpha$ ratio over the (R, v) diagrams (see also Bureau 1998). A detailed analysis of the line ratio lies beyond the scope of this paper. However, as far as can be ascertained, the $\text{H}\alpha$ emission line shows identical structure to the [NII] line, providing further evidence that the structure cannot be attributed to the details of the gas' ionization state.

In summary, this spectral study of edge-on galaxies quite firmly establishes the link between boxy bulges and galactic bars. However, we have only just begun to tap into the wealth of information that the spectra provide. Modelling the full complexity of spectral data such as those shown in Fig. 1 should yield a wealth of information about barred galaxies, allowing

us to map out their complete three-dimensional structure for the first time.

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