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Peanut-shaped bulges in face-on disk galaxies

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Abstract. We present high resolution absorption-line spectroscopy of 3 face-on galaxies, NGC 98, NGC 600, and NGC 1703 with the aim of searching for box/peanut (B/P)-shaped bulges. These observations test and confirm the prediction of Debattista et al. (2005) that face-on B/P-shaped bulges can be recognized by a double minimum in the profile of the fourth-order Gauss-Hermite moment h_4. In NGC 1703, which is an unbarred control galaxy, we found no evidence of a B/P bulge. In NGC 98, a clear double minimum in h_4 is present along the major axis of the bar and before the end of the bar, as predicted. In contrast, in NGC 600, which is also a barred galaxy but lacks a substantial bulge, we do not find a significant B/P shape.

Key words. galaxies: bulges – galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics – galaxies: structure

1. Introduction

Understanding how bulges form is of great importance to develop a complete picture of galaxy formation. The processes by which bulges form are still debated. On the one hand, the merger of dwarf-sized galactic subunits has been suggested as the main path for bulge formation (Kauffmann et al. 1993), which is supported by the relatively homogeneous bulge stellar populations of the Milky Way and M31 (Zoccali et al. 2003). Bulges formed in such mergers are termed 'classical' bulges. Alternatively, bulges may form via internal 'secular' processes such as bar-driven gas inflows, bending instabilities, clump instabilities, etc. (Combes & Sanders 1981; Debattista et al. 2006). Evidence for secular bulge formation includes the near-exponential bulge light profiles (Andredakis & Sanders 1994), a correlation between bulge and disk scale lengths (MacArthur et al. 2003; Méndez-Abreu et al. 2008a), the similar colors of bulges and inner disks (Peletier & Balcells 1996), substantial bulge rotation (Kormendy & Kennicutt 2004), and the presence of box/peanut (B/P)-shaped bulges in ∼ 45% of edge-on disk galaxies (Lütticke et al. 2000). A review of secular 'pseudo-bulge' formation and evidence for it can be found in Kormendy & Kennicutt (2004). Standard cold dark matter cosmology predicts that galaxies without classical bulges

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should be rare (D'Onghia & Burkert 2004). Not only are they not rare in nature, but the formation of pseudo-bulges means that some fraction of bulged galaxies lack a classical bulge, exacerbating the disagreement between theory and observations (Debattista et al. 2006). It is therefore important to determine which bulges are of the classical versus pseudo variety, and which are a mix of both.

Of primary concern here, several pieces of evidence point to the identification of most B/P bulges in edge-on spiral galaxies with the bars of barred spirals. N-body simulations show that barred galaxies have a tendency to develop B/P bulges. The observed incidence of B/P bulges is consistent with that expected if they are associated with relatively strong bars. A recent work by Lütticke et al. (2000) demonstrated that 45% of all bulges are B/P, while amongst those the shape of the bulge depends mainly on the viewing angle to the bar. As shown by the numerical simulations, true peanuts are bars seen side-on, that is, with the major-axis of the bar perpendicular to the line of sight. For less-favourable viewing angles, the bulge/bar looks boxy, and if the bar is seen end-on it looks almost spherical.

The presence of bars in edge-on galaxies with B/P bulges has been observationally established by the kinematics of gas and stars (see Bureau & Athanassoula 2005, and references therein). The kinematics of discs harbouring a B/P bulge, as measured from both ionized-gas emission lines and stellar absorption lines, show the behaviour expected of barred spirals viewed edge-on. However, the degeneracy inherent in deprojecting edge-on galaxies makes it difficult to study other properties of the host galaxy. For example, simulations show that a bar can produce a B/P shape even if a massive classical bulge formed before the disk (Debattista et al. 2005). Understanding the relative importance of classical and pseudo-bulges requires an attempt at a cleaner separation of bulges, bars and peanuts, which is easiest to accomplish in less inclined systems.

Recently, Debattista et al. (2005) proposed a kinematic diagnostic of B/P bulges in face-on ($i < 30°$) galaxies, namely a double minimum in the fourth-order Gauss-Hermite moment, h_4, along the major-axis of the bar. These minima occur because at the location of the B/P shape, the vertical density distribution of stars becomes broader, which leads to a double minimum in z_4, the fourth-order Gauss-Hermite moment of the vertical density distribution. The kinematic moment h_4 is then found to be an excellent proxy for the unobservable z_4. In contrast, the increase in the vertical scale-height does not produce any distinct signature of a B/P bulge and the vertical velocity dispersion, σ_z, is too strongly dependent on the radial density variation to provide a useful B/P bulge diagnostic. Debattista et al. (2006) showed that the diagnostic continues to hold even when gas is present since this sinks to a radius smaller than that of the B/P bulge.

This new kinematic diagnostic has been confirmed observationally by Mendez-Abreu et al. (2008b). Their main results are given here.

2. Observations, data-reduction and analysis

The barred galaxies NGC 98 and NGC 600 were selected as bright and undisturbed galaxies with a low inclination, a large bar, and modest extinction in the bar. The nearly face-on unbarred galaxy NGC 1703 was added as a control object.

The spectroscopic observations were carried out in service mode at the Very Large Telescope (VLT) at the European Southern Observatory (ESO) using The Focal Reducer Low Dispersion Spectrograph 2 (FORS2). The spectra were taken along the bar major axis of NGC 98 and NGC 600 and along the disk major axis of NGC 1703. The total integration time for each galaxy was 3 hours, in four exposures of 45 minutes each. Using standard IRAF routines, all the spectra were bias subtracted, flat-field corrected, cleaned of cosmic rays, corrected for bad pixels, and wavelength calibrated. The instrumental resolution was 1.84 ± 0.01 Å (FWHM) corresponding to $\sigma_{inst} = 27$ km s^{-1} at 8552 Å.

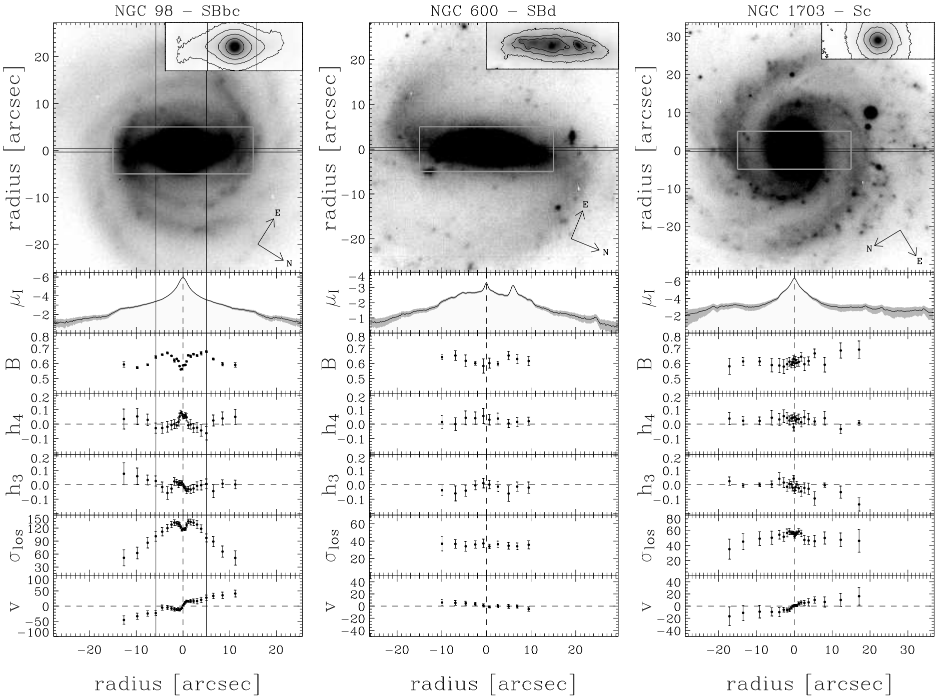

Fig. 1. Morphology and stellar kinematics of NGC 98 (left panels), NGC 600 (central panels), and NGC 1703 (right panels). For each galaxy the top panel shows the VLT/FORS2 R−band image. The slit position and image orientation are indicated. The inset shows the portion of the galaxy image marked with a white box. The gray scale and isophotes were chosen to enhance the features observed in the central regions. The remaining panels show from top to bottom the profiles of surface density, $\mathcal{B}(0.7, 0.9)$, h_4, h_3, σ, and mean velocity after the subtraction of the systemic velocity, v. The two vertical lines indicate the location of the h_4 minima in NGC 98.

2.1. Photometry

We analyzed the uncalibrated acquisition images from the VLT to derive the photometric properties of the sample galaxies. Isophote-fitting with ellipses, after masking foreground stars and bad pixels, was carried out using the IRAF task ELLIPSE. Under the assumption that the outer disks are circular, their inclination was determined by averaging the outer isophotes. All 3 galaxies have $i < 30°$. The semi-major axis length, $a_{\rm B}$ of the two bars was measured from a Fourier decomposition as in Aguerri et al. (2000).

2.2. Kinematics

The stellar kinematics of the three galaxies were measured from the absorption features present in the wavelength range centered on the CaII triplet ($\lambda\lambda$ 8498, 8542, 8662 Å) using the Penalized Pixel Fitting method (pPXF, Cappellari & Emsellem 2004). The spectra were rebinned along the dispersion direction to a logarithmic scale, and along the spatial direction to obtain a signal-to-noise ratio $S/N \gtrsim 40$ Å^{-1}.

A linear combination of the template stellar spectra, convolved with the line-of-sight velocity distribution (LOSVD) described by a Gauss-Hermite expansion (Gerhard 1993; van der Marel & Franx 1993) was fitted to each galaxy spectrum by χ^2 minimization in pixel space. This allowed us to derive profiles of the mean velocity (v), velocity dispersion (σ), third (h_3), and fourth-order (h_4) Gauss-Hermite moments. The uncertainties on the kinematic parameters were estimated by Monte Carlo simulations with photon, read out and sky noise. Extensive testing on simulated galaxy spectra was performed to provide an estimate of the biases of the pPXF method with the adopted instrumental setup and spectral sampling. The simulated spectra were obtained by convolving the template spectra with a LOSVD parametrized as a Gauss-Hermite series and measured as if they were real. No bias was found in the ranges of S/N and σ which characterize the spectra of the sample galaxies. The values of h_3 and h_4 measured for the simulated spectra differ from the intrinsic ones only within the measured errors (see also Emsellem et al. 2004).

3. Conclusions

We have identified for the first time a B/P-shaped bulge in a face-on galaxy. In the unbarred galaxy NGC 1703 we had not expected to find a B/P bulge and we included it in our sample as a control. The failure to find a double-minimum in h_4 is therefore fully consistent with previous results (Chung & Bureau 2004). Of the two barred galaxies, NGC 98 has clear evidence of a B/P bulge while NGC 600 does not. The absence of a B/P shape in this galaxy is not surprising since it appears to not have a bulge. If we identify the radius of the B/P bulge, $r_{\rm bp}$, with the location of the minimum in h_4, as found in simulations (Debattista et al. 2005), then we find $r_{\rm bp} = 0.35\ a_{\rm B}$, where $a_{\rm B}$ is the bar semi-major axis. Similarly, Kormendy & Kennicutt (2004) noted that the maximum radius of the boxy bulge is about one-third of the bar radius. Simulations also produce B/P-bulges which are generally smaller than the bar . Since B/P bulges are supported by resonant orbits, it would be very instructive to measure this ratio for a sample of barred galaxies.

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