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A SAURON look at galaxy bulges

J. FALCÓN-BARROSO[1], R. BACON[2], M. BUREAU[3], M. CAPPELLARI[1], R. L. DAVIES[4], E. EMSELLEM[2], D. KRAJNOVIĆ[1], H. KUNTSCHNER[5], R. MCDERMID[1], R. F. PELETIER[6] and P. T. DE ZEEUW[1]

[1] Sterrewacht Leiden, Niels Bohrweg 2, 2333 CA, Leiden, The Netherlands
[2] Centre de Recherche Astronomique de Lyon, 9 Avenue Charles–André, 69230 Saint-Genis-Laval, France
[3] Columbia Astrophysics Laboratory, 550 West 120th Street, 1027 Pupin Hall, MC 5247, New York, NY 10027, U.S.A.
[4] Denys Wilkinson Building, University of Oxford, Keble Road, Oxford, United Kingdom
[5] European Southern Observatory, Karl Schwarzschild Strasse 2, D-85748 Garching, Germany
[6] Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV Groningen, The Netherlands

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Abstract. Kinematic and population studies show that bulges are generally rotationally flattened systems similar to low-luminosity ellipticals. However, observations with state-of-the-art integral field spectrographs, such as SAURON, indicate that the situation is much more complex, and allow us to investigate phenomena such as triaxiality, kinematic decoupling and population substructure, and to study their connection to current formation and evolution scenarios for bulges of early-type galaxies. We present the examples of two S0 bulges from galaxies in our sample of nearby galaxies: one that shows all the properties expected from classical bulges (NGC 5866), and another case that presents kinematic features appropriate for barred disk galaxies (NGC 7332).

Key words: galaxies: evolution – galaxies: formation – galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – galaxies: individual (NGC 5866, NGC 7332)

1. Introduction

Lying at the centre of galaxies, bulges are a keystone in our understanding of galaxy formation and evolution. When studying their formation, one is often drawn to examine the order of events during galaxy assembly. In a simplistic approach, either the bulge formed before the disk, or the bulge formed from disk material.

Classical bulges are traditionally understood as spheroids with an $r^{1/4}$ surface brightness profile, in most ways identical to elliptical galaxies of the same luminosity. For example, bulges behave like ellipticals in the widely known scaling relations (Faber & Jackson 1976; Terlevich et al. 1981; Djorgovski & Davis 1987; Dressler et al. 1987). Kinematically, bulges, like low-luminosity ellipticals, are found to be isotropic oblate rotators (Kormendy & Illingworth 1982). Such analogies lie at the heart of merger-driven bulge formation models, in which the bulge formed before the disk.

Dynamicists, however, have shown in their numerical simulations that disk instabilities can pump disk material above the plane, thus generating central structures that also *bulge* over the thin disk (e.g. Hasan, Pfenniger & Norman 1993). These simulations raised the possibility of an alternative formation scenario in which bulges are formed via secular evolution processes after the disk (e.g. Pfenniger 1993). The presence of bars inside peanut-shaped bulges has been confirmed photometrically (Lütticke, Dettmar & Polhen 2000) and spectroscopically (Kuijken & Merrifield 1995; Bureau & Freeman 1999; Merrifield & Kuijken 1999). Furthermore, some bulges share strong similarities with disks, on the basis of their low velocity dispersions. The disky nature of bulges is usually discussed in relation to late-type, low-mass bulges (Kormendy 1993, Carollo 1999).

Do bulges come in two flavours, early-types forming in mergers and late-types through disk instabilities? To answer this question, it is vital to increase our knowledge on the structural and dynamical properties that link galaxy bulges to either slowly rotating spheroids akin to elliptical galaxies, or to rapidly-rotating flattened systems more nearly resembling the products of internal disk transformations.

Advances and discoveries in astrophysics often come together with instrument developments. Photometrically, the detailed pictures HST provided during the last decade, has revealed a large variety of features (e.g. inner disks or bars)

Correspondence to: jfalcon@strw.leidenuniv.nl

at the centre of galaxies (Lauer et al. 1995; Carollo 1999; Balcells et al. 2003). Spectroscopically, however, it is the ground-based integral field units (IFUs) that can map the full 2D stellar and gas kinematic signatures of those structures. This allows us to impose tighter constraints on the processes involved in the formation and evolution of galaxies.

The SAURON survey is a scientific project aiming to understand the formation and evolution of elliptical and lenticular galaxies and of spiral bulges from 2D observations of a representative sample of E/S0 galaxies and Sa bulges, using a custom-built panoramic integral field spectrograph placed at the 4.2m WHT on La Palma (Spain). Our early results (Bacon et al. 2001; de Zeeuw et al. 2002; Emsellem et al. 2003) reveal a variety of structures much richer than usually recognized in E/S0s galaxies.

We are carrying out a number of collaborative projects to investigate also bulges of later type (e.g. Sbc). These are taken from the samples of Balcells & Peletier (1994) and Carollo et al. (1997), which have extensive HST imaging available and in some cases also long-slit spectroscopy (e.g. Carollo et al. 2002; Balcells et al. 2003; Falcón-Barroso et al. 2003a).

Here we present two examples of galaxy bulges observed with SAURON. One case (NGC 5866) shows all the signatures expected on a classical bulge (see Sec. 1), whereas the second one (NGC 7332) presents properties of barred disks galaxies.

2. NGC 5866: a classical bulge

NGC 5866 is an edge-on S0 galaxy that has been studied in some of the most recent surveys of galaxies (Filho, Barthel & Ho 2002; McMahon et al. 2002; Terlevich & Forbes 2002; Jarrett et al. 2003). NGC 5866 shows a large bulge and an edge-on disk with a prominent dust lane (Fig. 2). The multi-slit analysis of its stellar kinematics shows a smoothly rising, featureless rotation curve (Fisher 1997), and the ionized-gas behaves like its stellar counterpart (Fisher 1997).

The power of the SAURON observations to obtain simultaneously 2D spatial and spectroscopic information allows us to show that the bulge and disk in NGC 5866 are separated both photometrically and kinematically. As expected in classical bulges, the disk is a flattened, rapidly rotating structure, while the bulge is a hotter, rounder and slower rotating component. The bulge does not rotate cylindrically, unlike the case of NGC 7332 (see below), but as normal spheroids. The large increase in the Hβ line index in the disk, compared to the bulge (see Fig. 2), means that the most recent stars formed in the disk. This age difference is also apparent from the decrease of the Mgb index. The combination of dynamical and stellar population models in this galaxy, but also for the others in the sample, will prove extremely important to put strong constraints on formation scenarios of bulges.

3. NGC 7332: a bulge made up from a bar

NGC 7332 is an ordinary looking edge-on S0 galaxy (Fig. 1) that has been extensively studied in the past. Photometric

Fig. 1. B-R-K composite images (Peletier & Balcells 1997) of NGC 5866 (left panel) and NGC 7332 (right panel).

analysis reveals a boxy bulge, a central disk and evidence for the presence of a 'weak' bar (Seifert & Scorza 1996; Lütticke et al. 2000). However, the galaxy is mainly known for a bright counter-rotating and a faint co-rotating [O III] gas component with respect to the stars (Bertola, Buson & Zeilinger 1992; Fisher, Illingworth & Franx 1994). Those gas structures were confirmed by Plana & Boulesteix (1996), who mapped the Hα emission via Fabry-Perot observations. NGC 7332 colours are somewhat bluer than those of elliptical galaxies of the same luminosity. Spectral analysis of the central regions reveals a luminosity-weighted age of about 6 Gyr (Vazdekis & Arimoto 1999).

The SAURON stellar kinematics (see Fig. 3) displays a rather smooth velocity field with rotation along the major-axis and a weak dependence of rotation on galactic height. The stellar kinematics also shows, for the first time, a decoupled component in the centre, misaligned with respect to the galaxy's kinematic major-axis, which may be related to a dip in the velocity dispersion map also in the centre (r $\lesssim$ 2$''$.5). As shown in Falcón-Barroso et al. (2003b), the gas exhibits very complex morphology and kinematics. This is found especially in [O III] which is again mainly counter-rotating with respect to the stars. The analysis of the absorption line-strengths reveal that NGC 7332's stellar populations are generally young (5 ± 2 Gyr), not only in the disk but also in the bulge, in agreement with previous studies (Balcells & Peletier 1994; Vazdekis et al. 1996; Terlevich & Forbes 2002). The metal absorption lines (e.g. Mgb) show an increase in the centre, contrasting with the rather homogeneous Hβ index. As emphasized by Falcón-Barroso et al. (2003b), the unique data set provided by SAURONprovides evidence for a formation scenario where both bar-driven processes and interactions play a significant role.

4. Conclusions

Bulges are not just simple scaled-down versions of elliptical galaxies. Instead, they often present properties closely related to bars or disks, that argue for different formation mechanisms. Integral field spectrographs have the ability to map the 2D behaviour of galaxies and allow us to characterize the full dynamical state of the bulges. Features like cylindri-

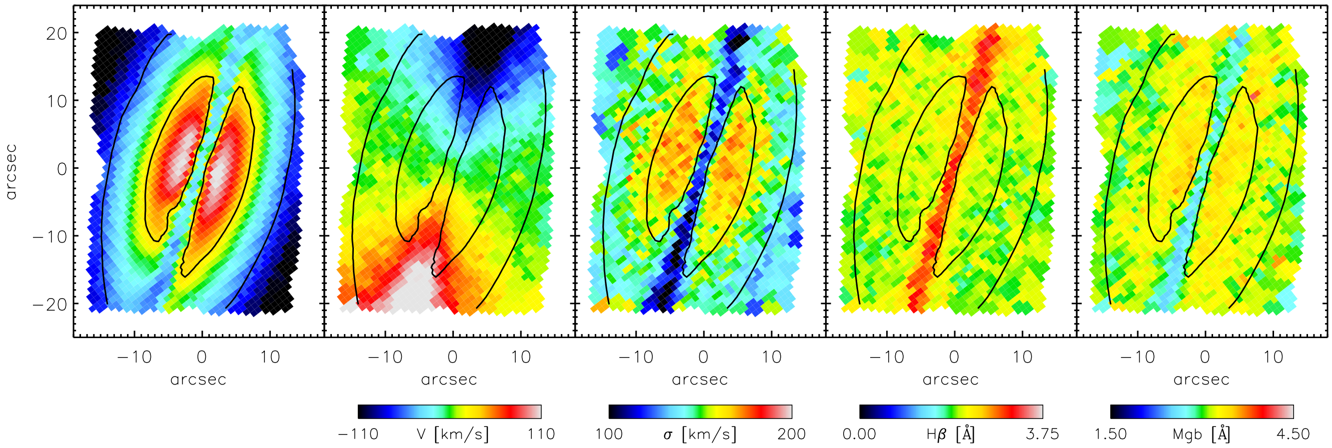

Fig. 2. SAURON maps of the S0/a galaxy NGC 5866. From left to right: integrated intensity, radial velocity of the stars, stellar velocity dispersion, Hβ and Mgb line-strength indices (both on the Lick system). The absorption line maps have been determined after separating absorption and emission (Emsellem et al. 2003; Falcón-Barroso et al. 2003b).

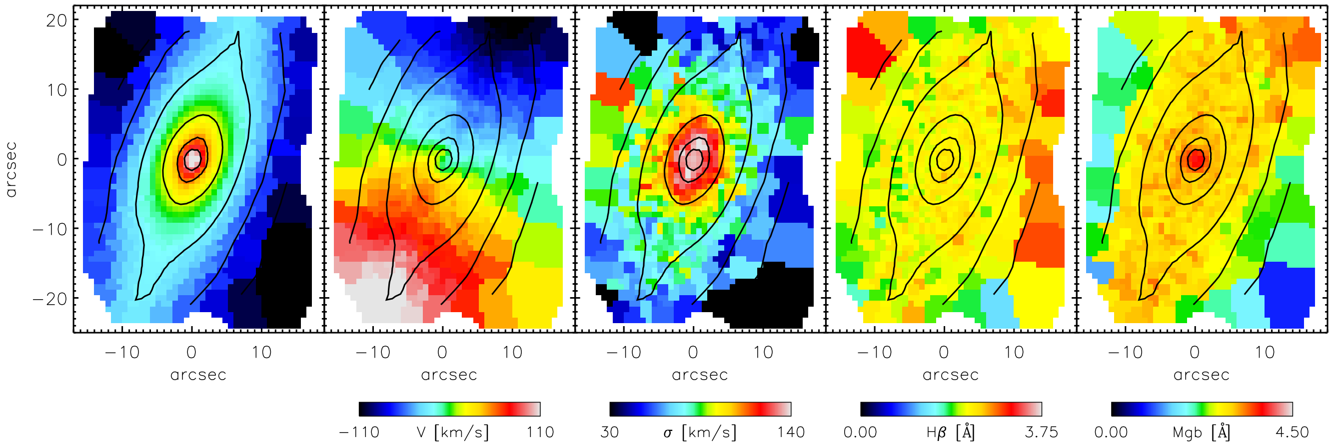

Fig. 3. SAURON maps of the S0 galaxy NGC 7332. From left to right: integrated intensity, radial velocity of the stars, stellar velocity dispersion, Hβ and Mgb line-strength indices (both on the Lick system). The absorption line maps have been determined after separating absorption and emission (Emsellem et al. 2003; Falcón-Barroso et al. 2003b).The SAURON spectra have been spatially binned to a minimum S/N of 60 by means of the Voronoi 2D binning algorithm of Cappellari & Copin (2003).

cal rotation, triaxiality, kinematic decoupling, bars, as well as the amount of rotational support as a function of distance above the plane can be easily studied. Furthermore, the line-strength maps contain essential information on the spatial distribution of the stellar populations, allowing us to determine global population gradients in the radial and vertical directions. All these capabilities, combined with dynamical and stellar population models, will provide unprecedented observational information that can be used to constrain the formation and evolution processes in bulges of galaxies.

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References

Bacon, R., Copin, Y., Monnet, G., et al.: 2001, MNRAS 326, 23
Balcells, M., Graham, A.W., Domínguez-Palmero, L., Peletier, R.F.: 2003, ApJ 582, L79
Balcells, M., Peletier, R.F.: 1994, AJ 107, 135
Bertola, F., Buson, L.M., Zeilinger, W.W.: 1992, ApJ 401, L79
Bureau, M., Freeman, K.C.: 1999, AJ 118, 126
Cappellari, M., Copin, Y.: 2003, MNRAS 342, 345
Carollo, C.M.: 1999, ApJ 523, 566
Carollo, C.M, Stiavelli, M., de Zeeuw, P.T., Mack, J.: 1997, AJ 114, 2366
Carollo, C.M, Stiavelli, M., Seigar, M., de Zeeuw, P.T., Dejonghe, H.: 2002, AJ 123, 159
Djorgovski, S., Davis, M.: 1987, ApJ 313, 59
Dressler, A., Lynden-Bell, D., Burstein, D., et al.: 1987, ApJ 313, 42
de Zeeuw, P.T., Bureau, M., Emsellem, E., et al.: 2002, MNRAS 329, 513

Emsellem, E., Cappellari, M., Peletier, R.F., et al.: 2003, submitted to MNRAS
Faber, S.M., Jackson, R.E.: 1976, ApJ 204, 668
Falcón-Barroso, J., Balcells, M., Peletier, R.F., Vazdekis, A.: 2003a, A&A 405, 455
Falcón-Barroso, J., Peletier, R.F., Emsellem, E., et al.: 2003b, submitted to MNRAS
Filho, M.E., Barthel, P.D., Ho, L.C.: 2002, ApJS 142, 223
Fisher, D.: 1997, AJ 113, 950
Fisher, D., Illingworth, G., Franx, M.: 1994, AJ 107, 160
Hasan, H., Pfenniger, D., Norman, C.: 1993, ApJ 409, 91
Jarrett, T.H., Chester, T., Cutri, R., Schneider, S.E., Huchra, J.P.: 2003, AJ 125, 525
Kormendy, J.: 1993, in IAU Symp. 153: Galactic Bulges Vol. 153, Kinematics of extragalactic bulges: evidence that some bulges are really disks. p. 209
Kormendy, J., Illingworth, G.: 1982, ApJ 256, 460
Kuijken, K., Merrifield, M.R.: 1995, ApJ, 443, L13
Lauer, T.R., Ajhar, E.A., Byun, Y.I., et al.: 1995, AJ 110, 2622
Lütticke, R., Dettmar, R.J., Pohlen, M.: 2000, A&A 362, 435
McMahon, R.G., White, R.L., Helfand, D.J., Becker, R.H.: 2002, ApJS 143, 1
Merrifield, M.R., Kuijken K.: 1999, A&A 345, L47
Peletier, R.F., Balcells, M.: 1997, New Astronomy 1, 349
Pfenniger, D.: 1993, in IAU Symp. 153: Galactic Bulges Vol. 153. p. 387
Plana, H., Boulesteix, J.: 1996, A&A 307, 391
Seifert, W., Scorza, C.: 1996, A&A 310, 75
Terlevich, A.I., Forbes, D.A.: 2002, MNRAS 330, 547
Terlevich, R., Davies, R.L., Faber, S.M., Burstein, D.: 1981, MNRAS 196, 381
Vazdekis, A., Arimoto, N.: 1999, ApJ 525, 144
Vazdekis, A., Casuso, E., Peletier, R.F., Beckman, J. E.: 1996, ApJS 106, 307