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Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
10.1017/S1743921308017894

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2007

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Peletier, R. F., Ganda, K., Falcón-Barroso, J., Bacon, R., Cappellari, M., Davies, R. L., de Zeeuw, P. T., Emsellem, E., Krajnović, D., Kuntschner, H., McDermid, R. M., Sarzi, M., & van de Ven, G. (2007). Spiral Galaxies in the SAURON Survey. *Monthly Notices of the Royal Astronomical Society*, *380*(2), 271-276. https://doi.org/10.1017/S1743921308017894

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Formation and Evolution of Galaxy Bulges
Proceedings IAU Symposium No. 245, 2007
M. Bureau, E. Athanassoula & B. Barbuy, eds.
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doi:10.1017/S1743921308017894

Spiral galaxies in the SAURON survey

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Abstract. We discuss some recent integral field spectroscopy using the SAURON instrument of a sample consisting of 24 early-type spirals, part of the SAURON Survey, and 18 late-type spirals. Using 2-dimensional maps of their stellar radial velocity, velocity dispersion, and absorption line strength, it is now much easier to understand the nature of nearby galactic bulges. We discuss a few highlights of this work, and point out some new ideas about the formation of galactic bulges.

Keywords. galaxies: spiral, galaxies: stellar content, galaxies: bulges

1. Introduction

One of the remarkable features of an image of a spiral galaxy is its central light concentration. The recent Spitzer Space Telescope images once again showed some beautiful examples of this, in particular the Andromeda galaxy (SSC 2006-14), the Sombrero (SSC 2005-11), M 51 (SSC 2004-19) and NGC 7331 (SSC 2004-12). On the images one sees that every galaxy has a central light concentration due to stellar light with relatively few features due to dust and star formation. This light concentration is known as a galactic bulge. In the old days bulges were known as old, metal rich, galaxy components (Whitford 1978). Nowadays, there are strong indications that there is at least a large population of galactic bulges which also contain younger stars. Details about this can be found in the long review by Kormendy & Kennicutt (2004). Since research on bulges is making fast progress, however, I would like to revisit some of the issues raised in this paper in the light of new observations that have been carried out by our group using the SAURON instrument (Bacon *et al.* 2001), on the 4.2m WHT at La Palma.

Although spiral galaxies have been studied much less than ellipticals, there is a considerable literature about the kinematics of stars and gas in the central regions of spirals, and also on the stellar populations in these objects. However, new insight can be obtained from the IFU-spectroscopy from SAURON, since it provides two-dimensional maps of several astrophysical quantities, which are much easier to interpret than one-dimensional profiles. At the same time, stellar populations can be combined *locally* with kinematics, and the sample of spirals can be compared easily with the large sample of nearby ellipticals

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observed with the same instrument. Since the instrument covers a large field of view on the sky, SAURON data are ideal to study the nature of galactic bulges, which, except for the largest nearby galaxies, rarely dominate the disc outside the central 10″. At the same time one can learn something about differences between bulge and inner disk.

In this proceedings we will discuss two samples of nearby galaxies: a sample of 24 S0/a-Sb galaxies, uniformly sampled in the luminosity - disk ellipticity plane, part of the SAURON Survey (de Zeeuw *et al.* 2002), and a sample of 18 late-type spirals (Sb-Sd), optically selected with radial velocity smaller than 3000 km/s. We will present a few highlights of a number of papers that we have published recently: the kinematics of gas and stars and the emission line strengths in the early-type spirals in Falcón-Barroso *et al.* (2006), the absorption line strengths of the same sample in Peletier *et al.* (2007), the stellar and gaseous kinematics and emission line strengths of the late-type sample in Ganda *et al.* (2006), and the absorption line strengths of the same sample in Ganda *et al.* (2007).

2. SAURON Observations of Spiral Galaxies

All spirals discussed here were observed using a single SAURON field of 33″ × 41″, sampled with lenslets of 0.94″ × 0.94″. Every lenslet provides a spectrum with a wavelength range from 4790 to 5300 Å, with a spectral resolution of 4.2Å FWHM. This spectral region contains several absorption lines useful for studying stellar populations, as well as the [OIII] emission line at 5007Å. For the spiral galaxies it is very important to separate the emission lines from the underlying absorption line spectrum. To do this, the spectra were fitted with a linear combination of stellar population models of Vazdekis (1999), and gaussian emission lines (for details about this procedure see Sarzi *et al.* 2006 and Falcón-Barroso *et al.* 2006). From the cleaned spectra we obtained the line indices Hβ, Mg b and Fe 5015.

In the way we described in Kuntschner *et al.* (2006) we determined ages, metallicities and abundance ratios at every position, assuming that the stellar populations there could be represented by a single-age, single metallicity stellar population. In practise, we determined the SSP for which the line strengths Fe 5015 , Hβ and Mg b fitted best in the χ^2 sense (Fig. 1). Although we know that it is a great over-simplification to represent the stellar populations (even locally) of a galaxy by a SSP, in some, especially elliptical galaxies this approach gives a good first-order approximation.

3. Stellar Populations in the Central Regions of Spiral Galaxies

As can be nicely seen in the unsharp masked HST images, almost all spirals are dusty in their central regions. This explains why it has been difficult to use colours as tracers of stellar populations. An exception might be the work of Peletier *et al.* (1999), who investigate colours of bulges for highly inclined galaxy on the dust-free side. The line strength maps show that young stellar populations are generally confined to a flat disk, with the young populations distributed in a compact nuclear region, a ring, or a large central area, the latter mostly in the faintest early-types or the late-type spirals. When analysing the central line strengths in the line strength – velocity dispersion diagram, one finds that the early-type spirals can be both young and old, while the late-type spirals clearly show a mix of stars of different ages.

Here we would like to concentrate on two aspects, the behaviour of line strength indices as a function of morphological type, and the central Mg/Fe ratio in spirals. In Figure 1 we show the three indices Hβ, Mg b and Fe 5015 as a function of morphological types,

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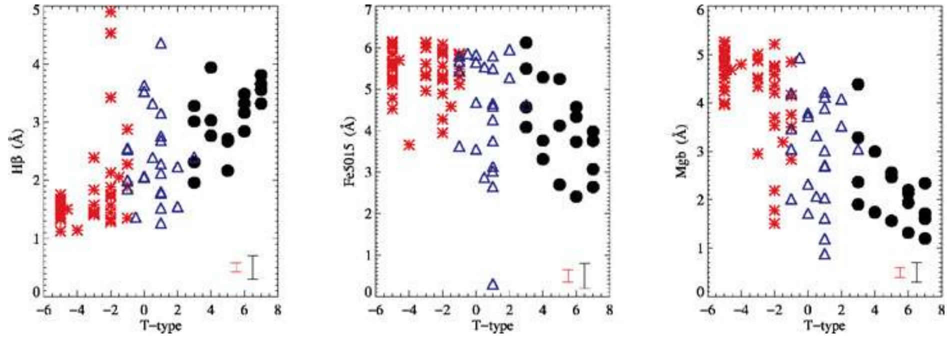

Figure 1. Several central line strength indices as a function of morphological type. Red asterisks are ellipticals and S0s from Kuntschner *et al.* (2006), blue triangles early-type SAURON survey spirals and black dots late-type spiral galaxies.

also plotting the SAURON sample of E and S0 galaxies (Kuntschner *et al.* (2006)). The lower envelope of the Hβ − type relation is filled with the oldest galaxies, while high Hβ values are found when a central burst of young stellar populations is present. In the two other diagrams the old stellar populations form an upper envelope, with young populations pushing the galaxies down. One can see that elliptical galaxies have rather uniform stellar populations, with little scatter. For S0 galaxies the same behaviour is seen, although there are a few outliers with strong central star bursts. For the Sa galaxies, we see a large range of central line indices, with the range decreasing towards the Sd galaxies. The figure shows that central star formation is star burst-like in early-type spirals, and is much more quiescent in late-type spirals. This agrees with the behaviour that is found when analysing Hα emission in spiral galaxies (Kennicutt 1998). It also shows that there is a continuity in central stellar population properties when going from early-type galaxies to the latest-type spiral galaxies, where some S0 galaxies are very similar to early-type spirals.

Figure 2 shows Fe 5015 as a function of Mg b. It shows that the central regions of elliptical and S0 galaxies have Mg/Fe ratios that are larger than solar (see Kuntschner *et al.* 2006 for more details), but also that especially late-type spirals lie on the SSP models with solar Mg/Fe ratios. Although our late-type spirals have stars with a considerable range in age and metallicity, it would still be very hard to have models for which Mg/Fe is larger than solar that agree with these observations. In fact, one expects late-type spirals, such as our Milky Way, to have solar Mg/Fe ratios. They indicate slow star formation, similar to what is happening in the solar neighbourhood. Both the bulge region and the inner disk have solar Mg/Fe ratios. One sees that the early-type spirals show a behaviour in between that of ellipticals and of late-type spirals, with more scatter.

4. Stellar Kinematics in Bulges - Sigma Drops

The (v/σ) − ϵ diagram has been a very powerful tool to characterise the nature of galactic bulges. Kormendy & Illingworth (1982) showed that bulges fall close to the oblate rotator line in this diagram, the line of an isotropic object flattened by its rotation. They, and also Davies et al. (1983), showed that kinematically, these bulges behave the same as intermediate mass ellipticals. The bulges for which kinematics was available at that time were all large bulges of early-type spirals. Later, Kormendy could add other bulges to the diagram, and found that some had larger (v/σ) than expected for an isotropic rotator,

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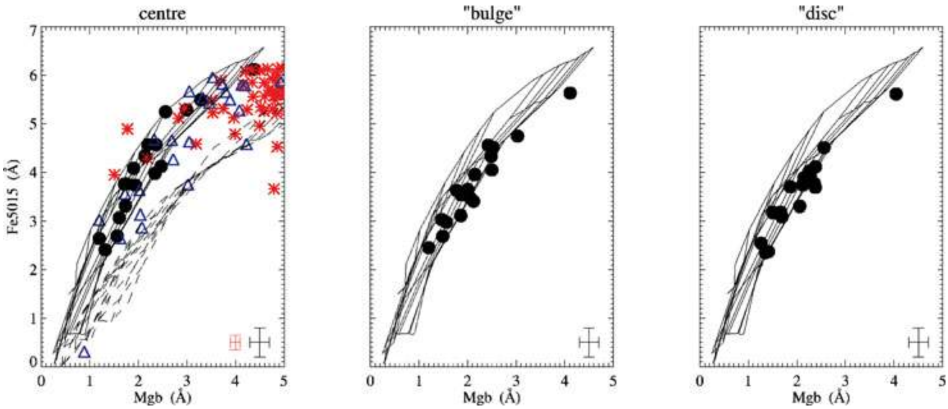

Figure 2. Index-index plots of Fe 5015 against Mg b, showing the [Mg/Fe] abundance ratios in the centres of the galaxies. Symbols as in Figure 1. Shown are model grids for single age-metallicity stellar populations, from Thomas et al. (2003), for [Mg/Fe]=0 (full lines) and [Mg/Fe]=0.5 (dashed lines). One sees that [Mg/Fe] for the late-type spirals is consistent with solar values. Plotted are the central line indices on the left, the bulge in the middle, and the disk, as covered by the SAURON field, on the right.

showing more disk-like kinematics, and considerably complicating our understanding of galactic bulges.

At present, we know about many galaxies in which a thin, rotating disk is dominating the light in the very inner parts, accompanied by a local minimum in the velocity dispersion. The first observed cases of central velocity dispersion minima date back to the late 80s and early 90s (e.g., Bottema 1989, 1993). Several others were found from long-slit data (Emsellem *et al.* 2001, Márquez *et al.* 2003). Now, SAURON observations show that 13 out of 24 Sa and Sab galaxies showed a central local minimum in the velocity dispersion (Fálcon-Barroso et al. 2006). Also, half the late-type spirals have local velocity dispersion minima in their centre, especially for the very latest types (Ganda *et al.* 2006). We see a weak trend that galaxies with sigma-drops are younger than those without (Peletier *et al.* 2007). The sigma-drops are probably due to central disks that formed from gas falling into the central regions through a secular evolution process. Simulations show that the disks will remain in place for a long time after they have been formed (Wozniak & Champavert 2006), although they will slowly heat up with time. Such central disks are also known among elliptical and S0 galaxies (e.g. NGC 4526, Emsellem *et al.* 2004, NGC 7332, Falcón-Barroso *et al.* 2004), but rare.

5. Our New Picture of Galactic Bulges

From our study of the stellar populations and kinematics of the central regions of spiral galaxies we infer that galactic bulges have more than one physical component: generally they contain a slowly-rotating, elliptical-like component, and one or more fast-rotating components in the plane of the galaxy, all co-existing in the same galaxies. This picture also nicely explains the fact that bulge populations in general are very similar to those in the disc (e.g. Peletier & Balcells 1996). In more than half of the SAURON early-type spirals sigma-drops occur. These correspond to central disks, which sometimes contribute most of the light corresponding to the bulge resulting from the photometric decomposition. HST images shows that the central disks correspond to dusty regions, often showing spiral structure. They also often, but not always, contain younger stellar populations than the regions outside the central disks.

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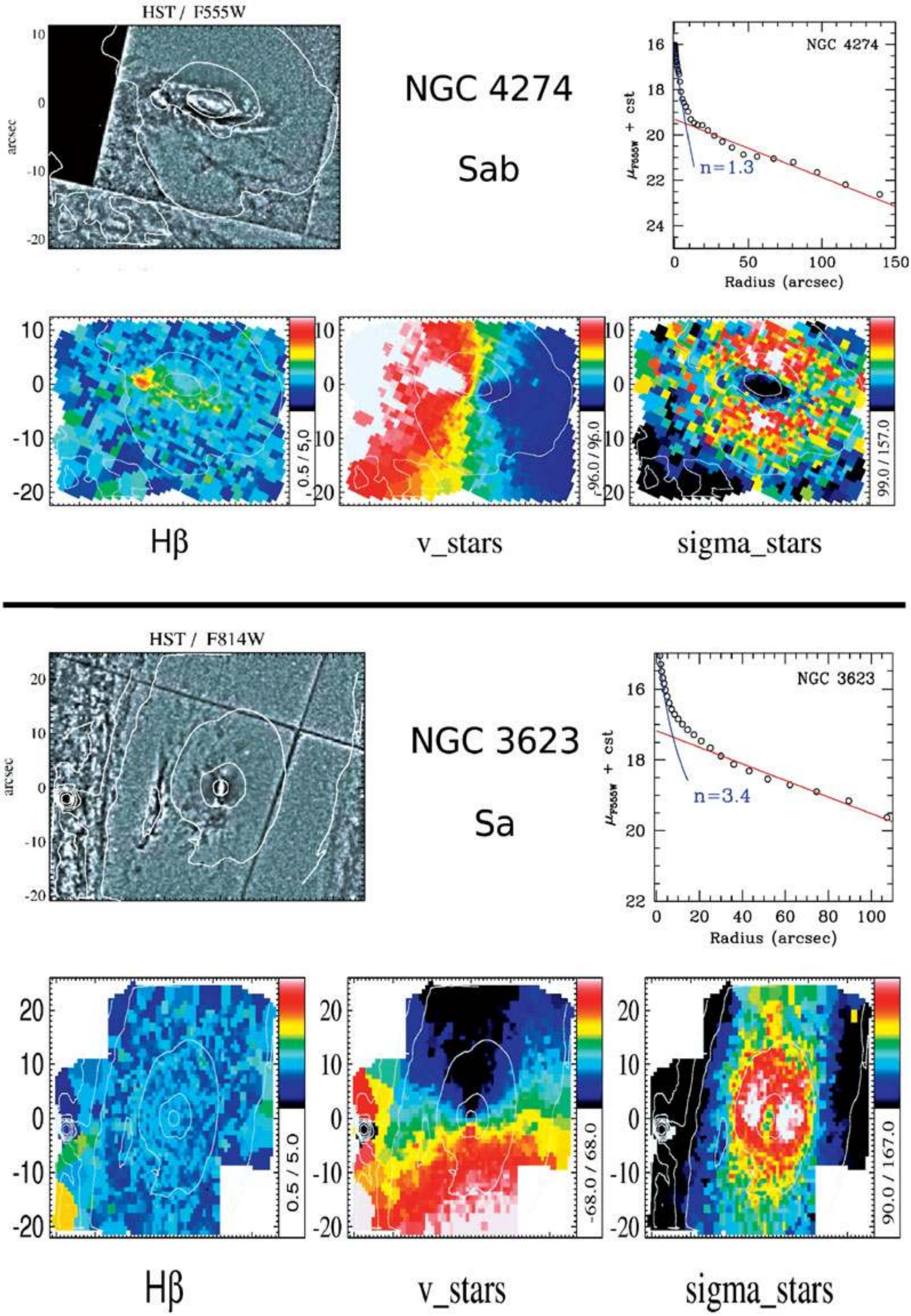

Figure 3. Diagnostic observations of NGC 4274 and NGC 3623, two early-type spirals. For each galaxy is shown in the top left: unsharp-masked F555W HST image, showing the places of non-negligible extinction (from Falcón-Barroso et al. 2006). Top right: major axis surface brightness profile, from the same HST data. A bulge-disk decomposition is also shown, with an exponential disk and a Sérsic bulge. Bottom row (from left to right): Hβ absorption line map (Peletier *et al.* 2007), stellar velocity and velocity dispersion map (Falcón-Barroso *et al.* 2006). Overlayed on all maps is the reconstructed SAURON intensity.

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We illustrate our picture using 2 galaxies (Fig. 3): The first one, NGC 4274, for which the surface brightness profile is fitted best by a Sérsic profile with n=1.3, has a strong sigma-drop. In the region where it dominates the stars rotate fast and have a low velocity dispersion (SAURON). Such an inner disc would be called a pseudo-bulge by Kormendy & Kennicutt (2004). It is dusty, has spiral structure (HST image) and shows younger stellar populations (SAURON). Note also that as one goes out on the minor axis, the stellar distribution becomes smooth, and the line strengths show values corresponding to old stellar populations. This region corresponds to an elliptical-like bulge, to which Kormendy & Kennicutt (2004) would refer as a classical bulge. NGC 4274 therefore would contain a pseudo-bulge *AND* a classical bulge. Making the classical bulge a bit larger, and the pseudo-bulge smaller, one gets an object such as NGC 3623 (bottom of Fig. 3). Here the spheroidal bulge dominates the light, apart from the very inner regions. A sigma-drop is seen, but weaker than in NGC 4274 (Falcón-Barroso *et al.* 2006). The Sérsic fit for the bulge gives n=3.4. Dust is associated with the central disks, but the SAURON maps show that the stellar populations in it are not different from the bulge outside it. The comparison between NGC 3623 and NGC 4274 shows that both objects are very similar, but that the inner disk to elliptical bulge ratio in both galaxies is different.

To conclude, we would like to point the reader to the similarities between elliptical and spiral galaxies. Not only can elliptical galaxies consist of several components (inner disks, KDCs etc.), the same can be the case for spiral galaxies, with their large, thin disk, thick disk, hot bulge, inner disk etc.

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