Two-dimensional kinematics and stellar populations of early-type galaxies: First results from the SAURON survey

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Abstract. We present the SAURON project, which is aimed at studying the morphology, two-dimensional kinematics and stellar populations of a representative sample of elliptical galaxies and spiral bulges. SAURON, a dedicated integral-field spectrograph that is optimized for wide-field observations and has high throughput, was built in Lyon and is now operated at the WHT 4.2m telescope. At present, we have observed approximately two thirds of the seventy-two sample galaxies with SAURON. A comparison with published long-slit measurements demonstrates that the SAURON-data is of equal or better quality, and provides full twodimensional coverage. The velocity and velocity dispersion fields exhibit a large variety of morphologies: from simple rotating systems to cylindrical, disky and triaxial velocity fields, bars and decoupled cores. Most of these kinematical signatures do not have counterparts in the light distribution. While some galaxies are consistent with axisymmetry, most are more complex systems than assumed previously. This suggests that the kinematical properties of nearby E/S0 galaxies do not agree with the often assumed simplistic two-family model, in which the giant non-rotating triaxial ellipticals are opposed to the fast-rotating axisymmetric faint ellipticals and S0s.
1. Introduction

The formation and evolution of galaxies is an important topic of study for the main next-generation space (e.g., NGST) and ground-based (e.g., VLT) telescopes. The coming decade will provide a wealth of high-quality observational data on high redshift galaxies. However, a full understanding of galaxy formation and evolution can only be achieved by completing our knowledge of the present status of galaxies.

According to the ‘standard’ scenario, elliptical galaxies and spiral bulges are the result of complex processes, including successive mergers and star formation events. Evidence for this scenario can be found by studying the intrinsic shapes and internal dynamics of these objects. In the past years, a number of photometric and spectroscopic studies using ground-based telescopes and HST were devoted to this. From these studies, two classes of spheroidal galaxies emerge:

- **Giant ellipticals.** These galaxies are red, have a high metal content and boxy isophotes, are supported by anisotropic velocity distributions and have triaxial figures. Their nuclear luminosity profiles have shallow cusps.

- **Low-luminosity ellipticals and spiral bulges.** These objects are blue, less metal rich, have disky isophotes, are flattened by rotation and have nearly-oblate shapes. Their central luminosity profiles show steep cusps.

Until recently, kinematical studies were conducted with long-slit spectrographs. The limited spatial coverage of these instruments is not sufficient to capture the complicated velocity fields of triaxial galaxies. Furthermore, the few two-dimensional kinematical observations that were obtained with previous integral-field spectrographs show more complexity than often assumed, even for objects that were supposedly axisymmetric (e.g. M31, Bacon et al. 2001 and references therein).

The SAURON project is aimed to study the morphology, two-dimensional kinematics and stellar populations of a representative sample of early-type galaxies. To achieve this goal we have designed and built a dedicated panoramic integral-field spectrograph and developed new software for data reduction, analysis and state-of-the-art modeling. Here we present the project and describe some preliminary results, with emphasis on the stellar kinematics. Other contributions to this volume present different aspects of the project, including preliminary results on line-strengths.

2. Instrument

The instrument is a lenslet integral-field spectrograph, similar to the TIGER (Bacon et al., 1995) and OASIS (Bacon et al., 2000) instruments that have been operated successfully at CFH. By contrast to OASIS, which is optimized for high spatial resolution, SAURON was designed to have a large field of view (Table 1). The instrument incorporates a system for obtaining simultaneous sky spectra to ensure accurate sky subtraction. SAURON was commissioned at the William Herschel Telescope in early February 1999 (Fig. 1).

The current spectral window is 4810–5340 Å, a wavelength range that contains absorption lines for stellar dynamical and line-strength measurements (Hβ,
Figure 1. **SAURON** at the Cassegrain focus of the William Herschel Telescope.

Mg and Fe) and emission lines for ionized gas studies (H$\beta$, [OIII]). The full spectral range of **SAURON** covers 4500–7200 Å.

| Table 1. **SAURON** specifications |
|-----------------------------------|
| **Telescope** | William Herschel (4.2m) |
| **Field of view** | 33″ × 41″ (LR) |
| | 9″ × 11″ (HR) |
| **Sampling** | 0′.94 (LR) |
| | 0′.27 (HR) |
| **Lenslets** | 1577 (of which 146 sky) |
| **Wavelength range** | 4810–5340 Å |
| **Spectral features** | H$\beta$, [OIII], Mg$b$, Fe5270 |
| **Total efficiency** | 14.7% |
| **Commissioned** | February 1999 at WHT |

3. **Data reduction**

The goal of the data reduction software is to produce uniformly reduced data of high quality. Depending on its size (expressed in terms of the effective radius $r_e$), a galaxy will be observed in (a series of) one, two or, in some rare cases, three or more telescope pointings. Every pointing is split in a number of individual exposures, thirty minutes each. This implies that the reduced data-set will consist of roughly 170,000 independent spectra, corresponding to a large volume of raw data (of the order of 100 Gb). We are currently in the process of building a dedicated pipeline to reduce this large data set in an efficient way.
To obtain a large field of view, the SAURON spectra are more densely packed than was the case for OASIS. This means that special attention had to be paid to the extraction of the spectra. We also developed tools to mosaic and merge datacubes. Furthermore, specific software for the spatial binning of spectra in two dimensions was developed, in order to obtain almost uniform signal-to-noise over the field of view (Cappellari & Copin, this conference).

4. Sample

We have built a complete sample of nearby E/S0/Sa of 327 galaxies, using the following constraints:

- radial velocity: \(cz < 3000 \, \text{km s}^{-1}\)
- declination: \(-6^\circ < \delta < 64^\circ\)
- \(|b| \geq 15^\circ\)
- absolute magnitude: \(M_B \leq -18\)

From this, we selected a representative sample of 72 galaxies by uniformly populating the absolute magnitude–ellipticity plane. The sample spans a large range of global and nuclear properties, covering over four magnitudes in brightness \(M_B\), 0.6 magnitudes in color \((B-V)_c\), 0.35 in central Mg\(_2\) index, a factor 100 in rotational support \((V/\sigma)^*\), a factor 10 in central cusp-slope brightness profile and a factor 1000 in black hole mass. Half of the representative sample is located in ‘cluster’ environments, while the other half is in a less dense environment.

At the time of this conference 53 of the 72 galaxies were observed (Fig. 2). The survey should be completed after the two scheduled runs of January and April 2002. The complete list of galaxies can be found in de Zeeuw et al. (2002).

5. Science verification

We have performed extensive scientific verifications to check the quality of the SAURON measurements. This analysis demonstrates that the SAURON data is of similar or even higher quality than the best published long-slit measurements (de Zeeuw et al. 2002). An example of such a comparison is shown in Fig. 3, where long-slit kinematics along the major and minor photometric axis of the SB0 galaxy NGC3384 (Fisher 1997) is compared with similar measurements from a simulated long-slit extracted from SAURON maps. The RMS deviation between the two data sets is 7 km s\(^{-1}\) in \(V\) and 8 km s\(^{-1}\) in \(\sigma\). The important advantage of the SAURON measurements, as illustrated by the kinematic maps of NGC3384 (Fig. 4), is that they are two-dimensional and homogeneous\(^\ddagger\).

6. Stellar kinematics

The stellar kinematical maps (line-of-sight velocity \(V\), velocity dispersion \(\sigma\) and the third and fourth order Gauss-Hermite moments \(h_3, h_4\)) display a rich variety

\(^\ddagger\)SAURON observations of NGC3384 are presented in Bureau et al (this conference).
Figure 2. Status of the SAURON sample in December 2001. Observed galaxies (filled symbols) are shown in red (E), blue (S0) and green (Sa). Galaxies not yet observed are represented with open symbols.

Figure 3. Comparison of the SAURON kinematics of the SB0 galaxy NGC3384 (dots) with long-slit measurements (open diamonds) by Fisher (1997). The major and minor axis measurements are shown in respectively the left and right panels.
of shapes. We have empirically classified them according to their morphology, distinguishing the following classes (the object name between the brackets refers to the corresponding panel in Fig. 5):

- **Normal.** The rotation axis and the line that joins the velocity extremes are aligned with the photometric minor and major axes, respectively. The velocity dispersion map generally exhibits a well-defined central peak (NGC2974).

- **Disk.** A stellar disk is clearly present in the velocity field. The velocity dispersion field shows a peak that is elongated perpendicularly to the rotation axis (NGC2549).

- **Cylinder.** The velocity field displays cylindrical rotation (NGC6501).

- **S-shaped.** The photometric minor axis and the rotation axis are misaligned in the center (NGC1023).

- **Kinematically decoupled core.** The velocity field shows a clearly located, well-defined and radical change in its shape and/or amplitude (NGC4365).

- **Strongly misaligned.** The kinematical axis is misaligned from the photometric minor axis. An example is the bar-type rotation where the kinematical axis in the center is aligned with the photometric major axis in the outer regions (NGC4477).

- **Complex.** The velocity and dispersion fields display unexpected features. This is generally due to the presence of multiple components in the line-of-sight velocity distribution, which cannot be taken properly into account by simple Gaussian fitting schemes.

We quantify these kinematical maps by means of a new tool, ‘kinemetry’, which extracts the relevant parameters from the velocity field (e.g., Copin et al. 2001). It is similar to the photometric ellipse fitting analysis that is often used to quantify the morphology of light distributions in early-type galaxies.

Fully general dynamical models for some of the sample galaxies are under construction. We use Schwarzschild’s method (Schwarzschild 1979, 1982, 1993), together with a Multi-Gaussian expansion of the light distribution (Monnet et
Figure 5. Examples of kinematical observations obtained with the SAURON instrument, for the galaxies NGC2974, NGC2549, NGC4365, NGC6501, NGC1023 and NGC4477. Three panels are shown for each galaxy: the reconstructed light distribution (left), the mean stellar velocity field (center) and the stellar velocity dispersion field (right). For reference, the isophote at 0.5 $r_e$ is superimposed on the kinematical maps; the scale is in arcsec.
al. 1992; Emsellem et al. 1994). The axisymmetric three-integral software that is used (van der Marel et al. 1998; Cretton et al. 1999) is fully general and makes no assumptions about the distribution function or degree of anisotropy.

We applied this powerful tool first to the SAURON observations of M32 (Verolme et al. 2002). We selected M32 as a test-case because of the availability of high-quality data, including FOS and STIS observations, and reliable (dynamical) estimates of its relevant properties (van der Marel et al. 1998). Our results illustrate the superiority of the two-dimensional SAURON-data over multiple position angle long-slit data: we find strong limits on the inclination angle, which is essentially unconstrained with long-slit data only.

Other examples of axisymmetric Schwarzschild models using SAURON data are given in this conference (NGC3377, Cretton et al.; NGC7332, Falcon et al.). An extension of the Schwarzschild software to triaxiality is nearly complete.

7. Preliminary conclusions

The SAURON survey is not yet completed, and the analysis of this large data set has only recently started. However, we can already draw a few preliminary conclusions. As shown in Fig. 5, stellar kinematical maps of early-type galaxies and spiral bulges exhibit a large variety of morphologies. While some are simple axisymmetric systems, most are more complex than often assumed. This confirms that two-dimensional spectroscopy is mandatory to measure the complex behaviour of stars and gas in these galaxies. Furthermore, most of these signatures do not have counterparts in the light distribution (see Fig. 5). This implies that information contained in the light distribution is unreliable and may even be misleading. We illustrate this point further in Fig. 6, where we show the velocity fields of four E/S0 galaxies with similar light distributions. It is clear that the kinematical behaviour is different for every object, ranging from a fast-rotating axisymmetric object (NGC524) to a slow and cylindrically rotating object (NGC6501), including a kinematically decoupled core (NGC4406) and an object with non-axisymmetric rotation (NGC4459).

A meaningful statistical analysis of the SAURON observations requires the complete sample and adequate tools such as kinemetry. However, there are already indications that the kinematical properties of nearby E/S0 galaxies do not correspond to the often assumed simplistic two-family model, in which the giant non-rotating triaxial ellipticals are opposed to the fast-rotating axisymmetric faint ellipticals and S0s. We will investigate this further by studying the statistical incidence of kinematically decoupled cores, stellar disks, and asymmetries, and by constructing detailed self-consistent models for individual galaxies. This is a challenging undertaking. In the first step towards this goal, we have successfully built an axisymmetric three-integral Schwarzschild model for M32 (Verolme et al. 2002). This work shows that the presence of the SAURON data helps to constrain the inclination of the galaxy, which was not possible by using long-slit observations only. Presently, we are developing a general triaxial Schwarzschild code, which will be applied to the many non-axisymmetric objects in the SAURON survey.

The SAURON observations are not limited to stellar kinematics only. They also provide line-strength and emission line maps (see Emsellem et al., this
confernce). Our aim is to combine all this information and thus gain more understanding of the current properties of normal early-type galaxies and to derive strong constraints on their formation and evolution. As an example, our study of the line-strength maps of NGC4365 show that its kinematical decoupled core (Fig. 1) is a long-lived structure that has almost the same age as the rest of the galaxy (Davies et al., 2001).

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