TITLE
ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR**
EDITORS

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

Roland Bacon[1], Martin Bureau[6], Michele Cappellari[5], Yannick Copin[7], Roger Davies[2], Eric Emsellem[1], Harald Kuntschner[3], Richard McDermid[2], Bryan Miller[8], Reynier Peletier[1,4], Ellen Verolme[5] & Tim de Zeeuw[5]

[1] *Centre de Recherche Astronomique de Lyon, Saint-Genis-Laval, France*

[2] *Physics Department, University of Durham, Durham, UK*

[3] *European Southern Observatory, Garching bei München, Germany*

[4] *Department of Physics and Astronomy, University of Nottingham, Nottingham, UK*

[5] *Sterrewacht Leiden, Leiden, The Netherlands*

[6] *Department of Astronomy, Columbia University, New York, USA*

[7] *Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

[8] *Gemini Observatory, La Serena, Chile*

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 and is 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 two-dimensional 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).

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 CFHT. 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, Mg and Fe) and emission lines for ionized gas studies (Hβ, [OIII]). The full spectral range of `SAURON` covers 4500–7200 Å.

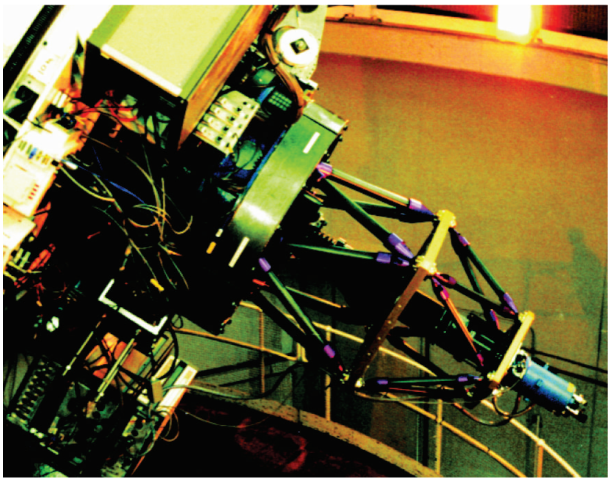

Figure 1. SAURON at the Cassegrain focus of the William Herschel Telescope.

Table 1. SAURON specifications

Telescope	William Herschel (4.2m)
Field of view	$33'' \times 41''$ (LR)
	$9'' \times 11''$ (HR)
Sampling	$0\farcs94$ (LR)
	$0\farcs27$ (HR)
Lenslets	1577 (of which 146 sky)
Wavelength range	4810–5340 Å
Spectral features	Hβ, [OIII], Mgb, 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

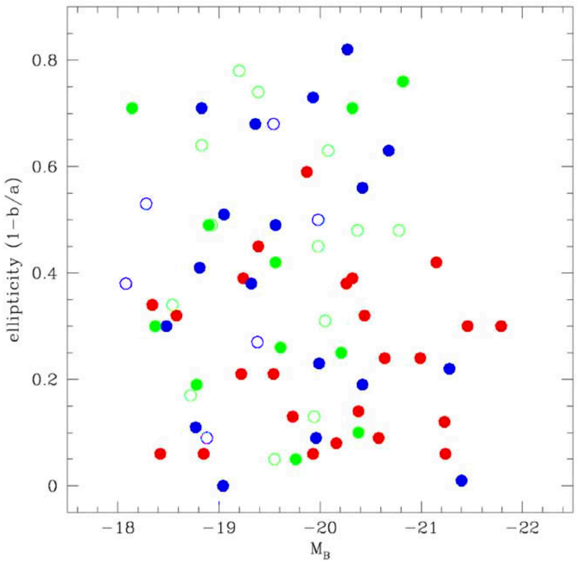

Figure 2. Status of the SAURON sample in December 2001. Observed galaxies (filled symbols) are shown in red (E), blue (S0) and green (Sa). Galaxies not yet observed are represented with open symbols.

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: $cz < 3000$ km s^{-1}
- declination: $-6^o < \delta < 64^o$
- $|b| \geq 15^o$
- absolute magnitude: $M_B \leq -18$

From this, we selected a representative sample of 72 galaxies by uniformely 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 $(B-V)_e$, 0.35 in central Mg_2 index, a factor 100 in rotational support $(V/\text{sigma})^*$, 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).

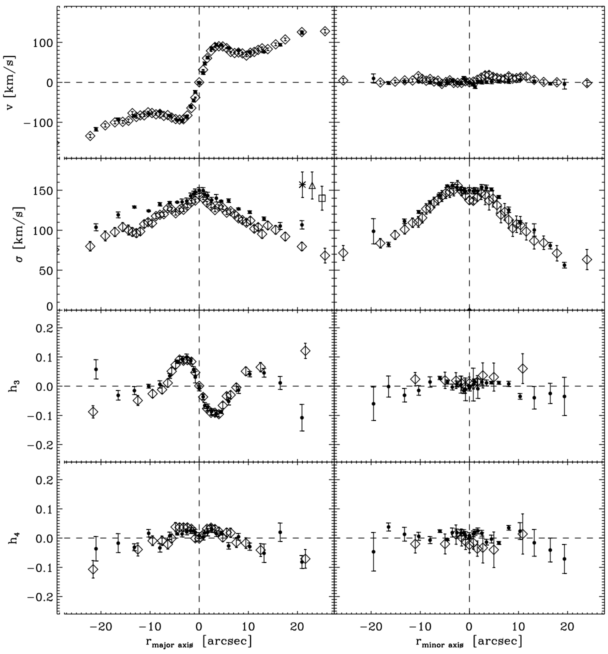

Figure 3. Comparison of the SAURON kinematics of the SB0 galaxy NGC3384 (dots) with long-slit measurements (open diamonds) by Fisher (1997). The major and minor axis measurements are shown in respectively the left and right panels.

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 $\mathrm{km\,s^{-1}}$ in V and 8 $\mathrm{km\,s^{-1}}$ in σ. 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[1].

6. Stellar kinematics

The stellar kinematical maps (line-of-sight velocity V, velocity dispersion σ and the third and fourth order Gauss-Hermite moments h_3, h_4) display a rich variety of shapes. We have empirically classified them according to their morphology,

[1]SAURON observations of NGC3384 are presented in Bureau et al (this conference).

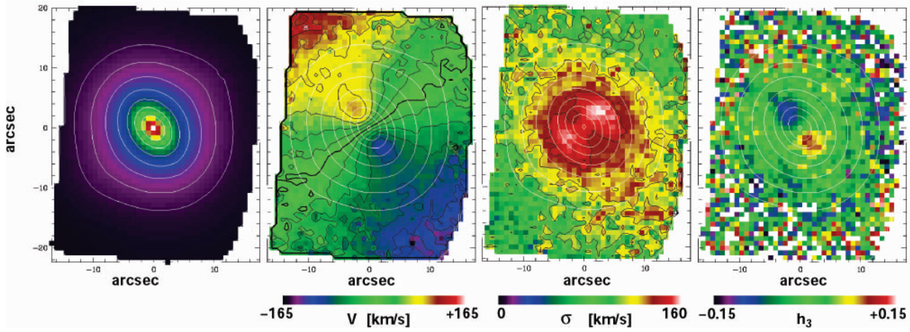

Figure 4. SAURON observations of NGC3384, based on a single pointing of four 30-minutes exposures. From left to right: the reconstructed total intensity, the mean stellar velocity, the stellar velocity dispersion and the Gauss-Hermite moment h_3.

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).
- **Triaxial**. The photometric minor axis and the rotation axis are misaligned (NGC1023).
- **Kinematically decoupled core**. The velocity field shows a clearly located, well-defined and radical change (NGC4365).
- **Bar**. The kinematical axis is misaligned from the photometric minor axis in the center and 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 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.

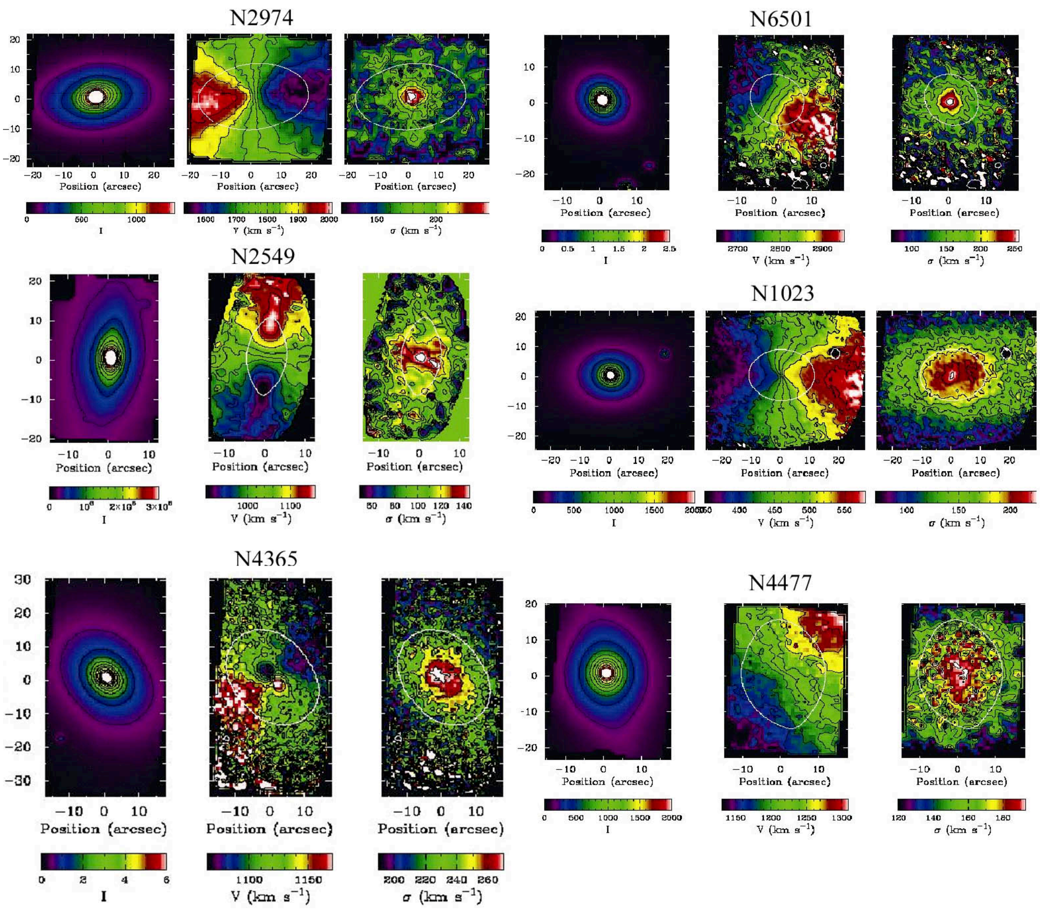

Figure 5. Examples of kinematical observations obtained with the `SAURON` instrument, for the galaxies NGC2974, NGC2549, NGC4365, NGC6501, NGC1023 and NGC4477. Three panels are shown for each galaxy: the reconstructed light distribution (left), the mean stellar velocity field (center) and the stellar velocity dispersion field (right). For reference, the isophote at 0.5 r_e is superimposed on the kinematical maps; the scale is in arcsec.

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, if not all, 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 Scharzschild 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 conference). 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

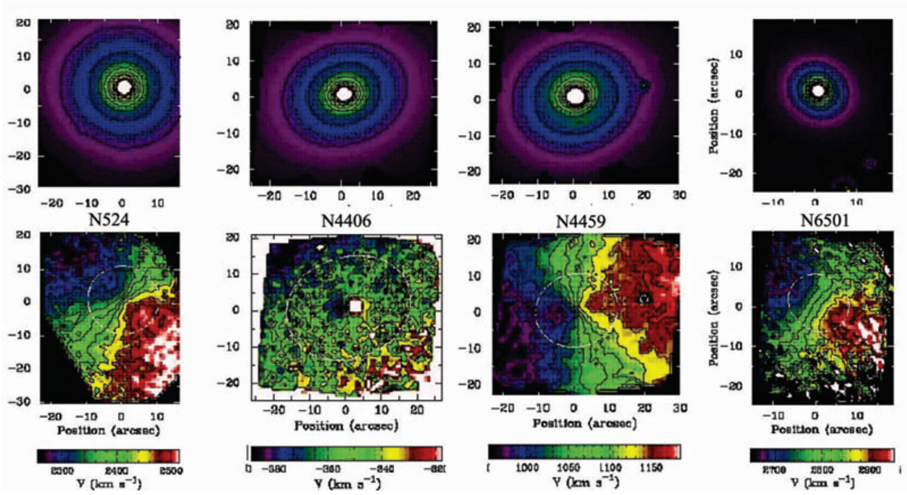

Figure 6. Examples of SAURON early-type galaxies that have similar morphology (upper panels), but very different mean stellar velocity field (lower panels). For reference, the isophote at 0.5 r_e is superimposed on the kinematical maps; the scale is in arcsec.

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).

References

Bacon R., Adam G., Baranne A., Courtes G., Dubet D., Dubois J.P., Emsellem E., Ferruit P., Georgelin Y., Monnet G., Pecontal E., Rousset A., Say F., 1995, A&AS, 113, 347

Bacon R., Emsellem E., Copin Y., Monnet G., 2000, in *Imaging the Universe in Three Dimensions*, eds W. van Breugel & J. Bland–Hawthorn, ASP Conf. Ser. 195, 173

Bacon R., Copin Y., Monnet G., et al. 2001, MNRAS, 326, 23

Bacon R., Emsellem E., Combes F., Copin Y., Monnet G., Martin P., 2001, A&A, 371, 409

Bureau M. et al, this conference

Cappellari M., Copin Y., this conference

Copin Y., Bacon R., Bureau M., Davies R.L., Emsellem E., Kuntschner H., Miller B.W., Peletier R.F., Verolme E.K., de Zeeuw P.T., 2001, SF2A 2001, eds F. Combes, D. Barret, F. Thévenin, EDPS Conf. Series in Astronomy & Astrophysics, 289–292

Cretton N., de Zeeuw P.T., van der Marel R.P., Rix H.-W., 1999, ApJS, 124, 383

Cretton N. et al., this conference

Davies R., Kuntschner H., Emsellem E., Bacon R., Bureau M., Carollo C.M., Copin Y., Miller B.W., Monnet G., Peletier R.F., Verolme E.K., de Zeeuw P.T., 2001, ApJL, 548, 33

Emsellem E., Monnet G., Bacon R., 1994, A&A, 285, 739

Emsellem E. et al., this conference

Falcon J. et al., this conference

Fisher D., 1997, AJ, 113, 950

van der Marel R.P., Cretton N., de Zeeuw P.T. & Rix H.-W., 1998, ApJ, 493, 613

Monnet G., Bacon R., Emsellem E., 1992, A&A, 253, 366

Schwarzschild M., 1979,, ApJ, 232, 236

Schwarzschild M., 1982, ApJ, 263, 599

Schwarzschild M., 1993, ApJ, 409, 563

Verolme E.K., Cappellari M., Copin Y., van der Marel R.P., Bacon R., Bureau M., Davies R.L., Miller B.M., de Zeeuw P.T., 2002, MNRAS, submitted (/astro-ph/0201086)

de Zeeuw P.T., Bureau M., Emsellem E., Bacon R., Carollo C.M., Copin Y., Davies R.L., Kuntschner H., Miller B.W., Monnet G., Peletier R.F., Verolme E.K., 2002, MNRAS 329, 513