Dynamics and morphology in the inner regions of spiral galaxies

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We present an introduction to the study of galactic disk dynamics, including specific aspects such as the effect of bar perturbations on rotating disks in connection with an existing active nucleus. This is followed by introducing the potential of Integral Field Spectrographs in this context, and presentation of the data set we analyse. We have observed a representative sample of 24 early-type (S0-Sab) spiral galaxies, equally divided between field and cluster members, with the SAURON Integral Field Spectrograph. Our observations provide the distribution and the full kinematic signatures of stars as well as gas, and the stellar population information over the central kpc.

The two-dimensional stellar line-of-sight-velocity distributions LOSVDs and gaseous emission-line kinematics, of the spiral galaxies, reveal the presence of multiple components and/or strong deviations from pure rotation. In this chapter, our main focus is the study of the gas velocity fields within the galactic disks, and to study the deviations from circular disk motions. We apply the harmonic decomposition to quantify the line-of-sight velocity information of the observed velocity maps. This type of analysis can be combined with pre-constructed models (see the studies of NGC 5448 and NGC 1068 in chapters 4 and 5), and provides clues about perturbations to the galaxy potential. One important aspect of this approach is to detect and quantify radial flows and understand the re-location of matter and fuelling of AGN by non-axisymmetric potentials. We find that in most cases, our analysis method is an excellent way to quantify the gas kinematic maps.

3.1 Introduction

A galactic disk is a highly flattened structure which contains most of the dynamically cold component of the galaxy. Disks are primarily rotating, but they exhibit a significant amount of random motions. Hence ordered rotational velocities are not the only observed kinematic signatures. Kinematic studies of the disks in external galaxies

This chapter contains preliminary results from the SAURON survey, which will be published in collaboration with the SAURON team.
have shown that all but face-on systems rotate with velocities much larger than the amount of random motions present. For external galaxies, one can obtain a direct measure of the random velocity component by extracting values of line-of-sight velocity dispersion $\sigma$ (see Sec. 3.3.1). The velocity dispersion provides a direct measure of the local surface density and it contributes to stabilising the galactic disk (Toomre 1964; Ostriker & Peebles 1973). Numerical simulations by Sellwood & Carlberg (1984) and Athanassoula & Sellwood (1986) have shown that velocity dispersion gives useful information about the stability and evolution of the disk. Collisional gas is expected to have settled in ordered motions, i.e., in a rotating disk, and its velocity dispersion may be affected by the gravitational potential of a central black hole or shocks and/or turbulence in the gas. HST/STIS data have been used to resolve these effects, but have not led to a quantification of their individual contributions to the gas velocity dispersions (Verdoes Kleijn, van der Marel & Noel-Storr 2004). The velocity dispersion of the gas normally increases towards the centre, reaching values similar to the central stellar velocity dispersion values (e.g., Zeilinger et al. 1996), although observations have shown that this is not always the case and that the central gaseous velocity dispersion is likely to exceed that of the stars (Ferrarese, Ford & Jaffe 1996; van der Marel & van den Bosch 1998; Cappellari et al. 2002). This is due to the significant effect of the central black hole. The velocity dispersion may also be affected by interactions and mergers. In such a case high random motions are theoretically expected (Walker et al. 1996) and the light profile of the merger remnants is changed (e.g., Schweizer 1980). Along these lines, once again the observed properties are indicative of different processes, and quantifying the relative contribution of each of these will bring significant advances to our understanding about galaxy formation and evolution.

When observing the central parts of disks one needs to be careful, since the light from the bulge is mixed with that from the disk, and obscuration by dust can obscure and/or distort the observed structures. However, the contribution from the bulge can be modelled by assuming that it is aligned with the disk. Allowing for gravitational influence from the disk, Kormendy & Illingworth (1982) have shown that a simple rotationally flattened bulge model is able to reproduce the observed kinematic and photometric properties of some bulges. This is, however, not always the case, since the nature of the bulges may vary significantly. Different formation processes are involved in bulge formation*, and the resultant will have different observational properties (Kormendy & Kennicutt 2004). It is important to estimate the relative role and time-scale of each of the formation processes to verify the degree of contamination of the light by the bulge.

*There are theories that bulges are formed by monolithic collapse (Eggen, Lynden-Bell & Sandage 1962); secular evolution (Combes et al. 1990; Kormendy 1993); or galaxy interactions (Toomre & Toomre 1972).
Figure 3.1: Schematic representation of the orientation dependent standard model of AGN. Different types of AGN hosts are observed depending on the viewing angle.

Observational as well as theoretical studies have revealed that the dynamics of disks is easily affected by external as well as internal factors. In this context, quantifying the observed kinematics is a necessary tool to understand the relative role of interaction with neighbouring systems and/or internal perturbations on the gravitational potential.

3.1.1 AGN

Within the range of galaxies, some contain nuclei of extraordinarily high luminosity. These sources are sometimes brighter than the rest of their host galaxy, and appear to originate from a small but highly active central region. This has been generally explained by accretion of material onto a supermassive black hole in the centre of the host galaxy. As the matter falls onto the black hole, large amounts of energy are released, creating a highly compact luminous central core, which is referred to as an Active Galactic Nucleus (AGN). There is a long discussion whether the emission in the centres of many galaxies is due to a point source in the nucleus or a starburst in an extended region about the centre. Lower luminosity AGN often need no accretion to be explained, as intense star formation can provide the dominant energy source (Terlevich et al. 1992). These objects are associated with galaxies with high rates of star formation, however, these explanations are not mutually exclusive.

Although all active galaxies emit their energy from within the central few parsecs, they exhibit different observational characteristics. There are several magnitudes of variation in the observed central luminosities, and a large variety of physical structures and sizes. Active galaxies are often classified in terms of their physical appearances and the radiation they emit. AGN are conventionally divided into radio galaxies, blazars, Seyfert galaxies, quasars, and Low-Ionisation Nuclear Emission
Region galaxies (LINERs) (e.g., Weedman 1970; Fanaroff & Riley 1974; Khachikian & Weedman 1974; Osterbrock 1977; Begelman, Blandford & Rees 1984; Filippenko 1996). The extension of these ideas has led towards the development of theoretical schemes and models which aim to explain the similarities and the differences observed between the different groups of AGN. Orientation dependent unification models have developed into a standard model (Antonucci & Miller 1985; Barthel 1991). Fundamentally, this model is based on the idea that a torus of gas and dust obscures the nuclear emission-line regions, producing different observed characteristics when viewed from different orientations (see Fig. 3.1 for an illustration of the unified model).

3.1.2 Bars

Some observed kinematic features in galaxy disks are indicative of the presence of motions superimposed on the rotational motions. The source of these may be external such as infalling matter, collisions or gravitational interaction with neighbouring systems. Other plausible triggers are perturbations on the gravitational potential of the galaxy. Although some perturbations may be due to interacting systems, here, we focus on the internal ones. These develop through time, and are believed to build up some prominent features such as spiral arms, rings, and bars. In turn, the built up features cause systematic distortions on the observed line-of-sight velocities.

Systematic distortions of the line-of-sight velocities of a gas, induced by spiral structures (Lin & Shu 1964; Lin, Yuan & Shu 1969) or bars (Lindblad 1964; Athanassoula & Sellwood 1986) are well known. To quantify these distortions, one pictures the disk as consisting of a large number of slowly deforming and rotating rings. Small changes with radius in the shape or orientation of these rings gives rise to regions of enhanced surface density as illustrated in Fig. 3.2. In the absence of self gravity, the initial pattern of the over densities winds up, since the time to complete one rotation becomes larger further out. Inclined rings exert gravitational torques on one another, causing the angular momenta and radial actions of the rings to slowly change. This
interaction is strongest when the rings are closer to each other and deforms the rings to some degree of strength. If self gravity is present, a wave of ring deformation propagates through the disk. A density wave has been formed. This may cause some of the orbital rings to intersect, but this causes no complications for the stellar particles within them. The stellar orbits are allowed to intersect, since the small cross section of stars ensures they will not collide. The gas, however, is sensitive to shocks and is not allowed to follow intersecting orbits. Picturing the gas as a continuous fluid has been favoured by the observation of noticeable dust lanes along spiral arms and bars (e.g., Kaufman et al. 1989). Simulations of bars have shown that the gas reveals a, predominantly trailing, spiral structure driven by the bar (Sanders & Huntley 1976). Periodic orbit families in a bar potential and their induced resonances can be used to interpret this by epicyclic motions (See Fig. 3.3). Stars within the bar follow epicyclic closed orbits, in the frame rotating with the bar (see Fig. 3.4). Neglecting gas pressure, the gas stream lines follow the stellar orbits. The gas stream lines are not allowed to intersect, and large-scale shocks may develop. Accordingly, the circulating interstellar matter is compressed, and may create young stellar associations which in turn ionise the gas.

The extent, nature, and properties of the spiral structure is governed by a series of resonances between orbital motion and the rotating potential. To understand the nature of these resonances, the disk can be assumed to be differentially rotating in the presence of, for instance, a weak bar. As outlined by Binney & Tremaine (1987), the study of the orbits can be reduced to a two-dimensional problem by exploiting the conservation of the vertical component of angular momentum. Assuming, in Cartesian coordinates, an axisymmetric potential $\Phi(R, z)$ to be symmetric about the plane $z = 0$, the motion of a star can be reduced to the motion of the star in a plane.
One defines the effective potential as \( \Phi_{\text{eff}} \equiv \Phi(R, z) + \frac{L_z^2}{2R^2} \), where \( L_z \) is the component
of the angular momentum along the vertical axis. A circular orbit has an angular
velocity
\[
\omega^2 = \frac{d\Phi}{R dR} = \frac{L_z^2}{R^4}.
\]
In epicyclic approximation theory, the motion of any particle can then be expressed
in first order by an epicyclic oscillation, of frequency \( \kappa \).
\[
\kappa^2 \equiv \frac{d^2 \Phi_{\text{eff}}}{dR^2} = \frac{d^2 \Phi}{dR^2} + \frac{3L_z^2}{R^4} = \frac{d^2 \Phi}{dR^2} + 3\omega^2 = R \frac{d\omega^2}{dR} + 4\omega^2.
\]
The general orbit is therefore the combination of a circle and an epicycle (cf. Fig. 3.3).
The bar creates a bi-symmetric gravitational potential, with a predominant \( m = 2 \)
component, which rotates in the galaxy with the pattern speed \( \Omega_p \) (cf. Fig. 3.3).
Transformation into cylindrical coordinates \((r, \theta, z)\), where \( z = 0 \), gives the equipo-
tential \((\Psi)\) in the rotating frame:
\[
\Psi = \Phi(r, \theta) - \frac{1}{2} \Omega_p^2 r^2,
\]
in the rotating frame, the effective angular velocity of a particle is \( \omega' = \omega - \Omega_p \).
There exist regions in the galaxy where \( \omega' = \frac{\kappa}{m} \), i.e., where the epicyclic orbits close
themselves after \( m \) loops. The corresponding stars are aligned with the perturbation
and closely follow it; they interact with it always with the same sign, and resonate
with it. These zones are the Inner and Outer Lindblad Resonances (ILR and OLR).
The ILR is located at the point at which \( \omega = \Omega_p - \frac{\kappa}{2} \) and the OLR is located where
\( \omega = \Omega_p + \frac{\kappa}{2} \). The bar enhances the radial amplitudes of the stellar orbits in the vicinity
of these resonances. Another fundamental resonance is the Corotation Resonance
(CR), which occurs where the circular angular velocity equals the angular velocity of
the bar (\( \omega = \Omega_p \)).

For a bar, the two main families of closed orbits are addressed as the \( x_1 \) and \( x_2 \)
orbits (Contopoulos & Papayannopoulos 1980). In a non rotating bar, the \( x_1 \) orbits
are parallel to the bar. However, when rotation is introduced, these become box orbits
in the shape of generalised ellipses, elongated along the major-axis of the bar. Near
the centre, the \( x_1 \) orbits are almost circular (see Fig. 3.4). As the size of an orbit
increases so does its axial ratio until it reaches a maximum at which point it starts to
decrease again. Furthermore, the orbits become nearly circular outside of the coro-
tation radius. The axial ratio and curvature of the \( x_1 \) orbits increases with increasing
total central density of bar. The \( x_2 \) orbits are those perpendicular to the bar, and they
mark the position of the ILR (Athanassoula 1992; see also Fig. 3.4). The existence
and extent of \( x_2 \) orbits has important consequences for the shape of the shock fronts
that probably cause dust lanes. The consequence for the gas distribution is motion of
Figure 3.4: Periodic orbits in a bar viewed in the rotating frame of a dissipative barred potential. The bar is oriented horizontally. The dashed circles indicate the locations of ILR, CR, and OLR. The gas tends to follow these periodic orbits, but is forced to precess more rapidly while losing energy and angular momentum. Note also how the orientation of the $x_1$ (outside ILR) and $x_2$ (inside ILR) orbits change when crossing the ILR.

gas from the far ends of the bar towards the centre, shocks at the intersection of the $x_1$ and $x_2$ orbits, accumulation of gas near and inside the $x_2$ orbits, and the formation of dust lanes along the leading $x_1$ orbits (Contopoulos & Mertzanides 1977). If, however, dissipative forces are present as in the gas dynamical case, the amplitudes will be damped and the orientation of the closed orbits of the gas will deviate from that of the bar and gradually twist when passing over a resonance and thereby form a spiral density wave pattern. For a more extensive study of the resonances and its implications on the orbital families, the reader is referred to Binney & Tremaine (1987).

Here we summarise some of the main characteristics:

1. A density wave cannot pass the ILR.
2. Orbit shapes change across the resonances.
3. Outside the ILR, $x_1$ orbits are parallel to the bar.
4. Inside the ILR, $x_2$ orbits are perpendicular to the bar.
5. Stellar rings can form at the CR and/or OLR.
6. Gas rings or disks and star formation form close to the ILR.
7. Gas is driven inwards to the ILR, and outwards to the ILR.
8. Dust lanes and star formation fade towards CR.

The bar potential affects the dynamics of the rest of the system. The majority of stars within the bar seem to follow epicyclic orbits. When gas pressure is neglected, the gas stream lines must nearly coincide with the stellar periodic orbits, but since gas is subject to internal friction, it reacts differently from the stars. The density wave requires gas, and studying the behaviour of gas in a barred potential is critical.
to fully understand bars. The first attempt to study gas in barred potentials was done with the continuous fluid model by Sanders & Huntley (1976). The simulations treat gas as test particles moving in a fixed bar potential, showing that the gas revealed a spiral structure driven by the bar. This behaviour can be interpreted with the help of periodic orbits families. The gas first follows the periodic orbits (e.g., $x_1$ and $x_2$), but since the gas stream lines are not allowed to cross, gas clouds will suffer enhanced collisions and their orbits will deform. Instead of experiencing sudden turns, they gradually turn, and form spiral arms (see the region outside CR in Fig. 3.4). This predicts that the arms will be more wound up in the presence of larger number of resonances. When there is no ILR, strong shocks can occur on the leading edges of the bar corresponding to offset dust lanes (Sanders & Tubbs 1980). When two ILRs exist, the gas response can be perpendicular to the stellar bar. The varying behaviour of gas depending on the bar perturbation characteristics may also form rings, inner spiral arms, and inner bars (e.g., Combes 1996).

**Bar Pattern Speed Determination**

Several methods have been suggested for deriving the pattern speed $\Omega_p$ of bars (e.g., Knapen 1999). Morphological features around the bar such as rings or starting points of spiral arms have been associated with the location of various resonances. Establishing the location of the resonances then lead to the $\Omega_p$ (e.g., Combes & Gerin 1985; Canzian 1993). Alternatively, kinematic data can be matched to hydrodynamic models with varying pattern speeds, and the best agreements will provide estimates of $\Omega_p$ (Sanders & Tubbs 1980). A considerable improvement in the $\Omega_p$ derivation was introduced by Tremaine & Weinberg (1984). The Tremaine-Weinberg method is model-independent. Accordingly, the pattern speed is derived by invoking the continuity equation to obtain the $\Omega_p$ from the kinematic properties. If a galaxy lies at an inclination $i$, and if Cartesian $x$ and $y$ axes are aligned parallel to its apparent major and minor axes respectively, in the rest frame of the disk, $\Omega_p$ can be determined from

$$\Omega_p \sin i = \frac{\int_{-\infty}^{\infty} l(x)(v_{\text{los}}(x) - v_0)\,dx}{\int_{-\infty}^{\infty} l(x)(x - x_0)\,dx} = \frac{\langle v_{\text{los}} \rangle - v_0}{\langle x \rangle - x_0},$$

where the nucleus of the galaxy is located at $x = x_0$, the integrals are performed along any cut parallel to the apparent major-axis, and $v_{\text{los}}(x)$ is the mean line-of-sight velocity of the stars at position of $x$ on the chosen axis. The heliocentric velocity of the system in $v_0$, and the angled brackets denote the average value of the velocity and position weighted by the luminosity of stars at each point $l(x)$. 


3.1.3 Bars and AGN

In an AGN, the energy source or the central engine is generally considered to be powered by accretion onto the central supermassive black hole (Lynden-Bell 1969). This is to happen within very small physical areas, and requires a central black-body of mass $10^6 - 10^9 \, M_\odot$ to accrete material at a rate of between $10^{-2} - 10^2 \, M_\odot/yr$. For most luminous Quasars the fuelling time-scale is $10 - 100 \, M_\odot/yr^{-1}$, and for typical Seyfert galaxies this time-scale is $\sim 0.2 \, M_\odot/yr^{-1}$ (Ho et al. 1997), and for low luminosity AGNs or LINERs this time-scale is $\sim 10^{-4} \, M_\odot/yr^{-1}$. Observations have shown that nuclear activity is not always going on, therefore does not require a continuous volume of fuel and hence is a transient phase in the life of some galaxies (Haehnelt & Rees 1993; Ho et al. 1997). A key question is what processes cause the material/fuel to lose its angular momentum and fall inwards towards the centre. In rotating systems, perturbations can cause the potential to become non-axisymmetric, and material can be forwarded to reach the central regions. Alternatively, interactions with external systems can give rise to tidal effects, which it turn participate in the mass transportation to the centre. It was suggested by Hummel et al. (1990) that, although it is straightforward to transport gas to within the central kiloparsec and induce enhanced star formation, it is more difficult to make the gas reach smaller scales required to fuel the AGN. Although interactions and bars may play a role in mass transport from the outer parts to central kiloparsec, the transport of gas into the nuclear regions (few parsec scale) is mainly dependent on the distribution of mass within the galaxy. The different mechanisms included in the sequence of processes which, at various stages and scales, contribute to the fuelling of AGN are well outlined in Fig. 3.5.

Non-axisymmetric potentials are efficient in transferring mass from outer parts of a galaxy into the inner regions (e.g., Schwarz 1984; Sellwood & Wilkinson 1993; Knapen et al. 1995). Bars are non-axisymmetric gravitational potentials which perturb gas and stars from circular orbits, and can transform angular momentum into gravitational torques promoting inter-cloud interactions. As a consequence of this, the gas will lose its angular momentum and be transferred down the bar towards the central regions (Shlosman, Frank & Begelman 1989). At the very centres of galaxies, near the AGN, bars can become unstable as the infalling mass accumulates (Norman et al. 1996), and eventually destroy themselves (Shen & Sellwood 2004). Consequently, the abilities of bars as a fuelling mechanism is limited. This theory has been extended by introducing multiple bars (nested bars), which can transfer mass to the central parsec scale regions (e.g., Maciejewski & Sparke 1999; Heller, Shlosman & Englmaier 2001; Laine et al. 2002). These results are far from observationally verified, since bars are observed to be more ubiquitous than AGN. Observational studies by Knapen et al. (2000) have found no correlation between excess of bars and AGN activity, and other studies have suggested that not all the gas reaches the...
Figure 3.5: Schematic representation of various processes that are involved in fuelling the AGN. Matter may pass towards either a supermassive black hole or a region of star formation, thus fuel the AGN or trigger a starburst. The approximate radial scales at which these take place are indicated on the left of the diagram. From Shlosman, Begelman & Frank (1990). Note the particular importance of gaseous bar instabilities for this picture.

Moreover, and in comparison with mass transfer by bars, the gas masses needed to fuel the AGN are small. Gas quantities of this order may be brought to the centre by inflow speeds that are of order a few solar masses per year (e.g., Wong & Blitz 2000).
Although efficient, perhaps bars are not sufficient for relocating mass within galaxies. There is now an increasing need for quantifying the observational effects of bars, and kinematic studies will bring important clues for improving our understanding.

### 3.2 Integral Field Unit Data

When carrying out slit spectroscopic studies of extended objects, one is limited to a one particular position angle. Obtaining spectra over a two-dimensional field is highly desirable, as then there is no need to select any particular axis. An Integral Field Unit (IFU) produces spectra over a two-dimensional field (e.g., Bacon et al. 1995; Weitzel et al. 1996; Allington-Smith et al. 1997). An IFU is very efficient for studying, e.g., stellar populations and kinematics of galaxies in the nearby and intermediate redshift universe. As summarised in Fig. 3.6, the major techniques for constructing efficient IFUs are: Lenslet arrays; Fiber or Fiber-Lenslet reformatters; and Image slicers. The concept of an image slicer (left column of Fig. 3.6) is the same as that of conventional slit spectroscopy, but using several slits at the same time. Fiber reformatters work such that a Fiber bundle is put at the telescope focus, which then leads the light from each spatial element into a spectrograph. The fiber bundle can also be put behind a lenslet array to increase the amount of light going into the spectrograph without losing resolution (middle column of Fig. 3.6). Alternatively, only a lenslet array (right column of Fig. 3.6) can be positioned at the telescope focus, and lead the light from each spatial element onto a spectrograph. All these configurations result in a datacube with \(x\) and \(y\) sky coordinates, and wavelength along the \(z\)-axis (see Fig. 3.6).

For the data presented in this thesis, we use the new instrument SAURON, built by R. Bacon and the SAURON team (see Bacon et al. 2001). Using the SAURON IFU configuration (see Fig. 3.6), the field of view is divided into numerous small segments by a microlens array. The resultant pupil images are then dispersed by a conventional spectrograph. The spectrograph output contains a number of individual spectra spread over the field. Each spectrum needs an adjustment to the dispersion direction to avoid overlaps. This adjustment also places limits on the length of each spectrum, and results in relatively inefficient use of the detector since clear gaps must be provided between adjacent spectra to avoid cross-talk. For extended objects, the system allows a large number of spatial samples to be obtained more efficiently than with fiber bundles. The obtained spectra can be used to produce an image in the observed waveband by collapsing each spectrum in the wavelength direction (see Fig. 3.7). Moreover, each individual SAURON spectrum contains emission as well as absorption line features. The stellar absorption lines can be used to derive the stellar LOSVDs and relative absorption line strengths, and the gas emission-lines contain information about the gas diagnostics and gas kinematics.

Extracting the kinematic information for each lens results in two-dimensional
Different Integral Field Unit Configurations

Figure 3.6: Schematic presentation of different IFUs, all resulting in a datacube. The SAURON spectrograph uses the middle configuration.

kinematic maps covering the entire field of view. Recent studies have demonstrated the utility of IFUs in studies of galactic dynamics. For instance, Verolme et al. (2002) compared mass models of M32 constrained by SAURON with models constrained only by data along 4 slits extracted from the full data set. They found that the mass model parameters including mass-to-light ratio, black hole mass, and in particular inclination were better constrained with the full two-dimensional data than with just the slits. In a preliminary analysis of the SAURON maps, de Zeeuw et al. (2002) showed that early-type galaxies display a variety of line-strength distributions and kinematic structure which appears richer than often assumed. Specific examples of minor-axis rotation, decoupled cores, central stellar disks, and non-axisymmetric and counter-
SAURON Observations

![Galaxy Image](image1)

![A SAURON Spectrum](image2)

![SAURON Reconstructed Image](image3)

**Figure 3.7:** A SAURON exposure delivers spectra over the entire area as indicated by the box on the left image. Each lens (the small diamond is shown as an example) delivers a spectrum. Each spectrum contains stellar absorption (Mg $\beta$ and H$\beta$), and gas emission lines (H$\beta$, [OIII] and [Nii]). Adding each spectrum in the wavelength direction (horizontal in the middle panel), one can reconstruct the broadband image of the galaxy (right).

Rotating gaseous disks were shown. It was also shown that the line-strength distributions appear to follow the surface brightness distribution closely. The provisional indication was that only a small fraction of these mainly early-type galaxies can have axisymmetric intrinsic shapes.

### 3.3 SAURON Observations

We have used SAURON on the 4.2m WHT at La Palma to observe a representative sample of nearby ellipticals, lenticulars and early-type spiral bulges, as well as some objects with known peculiar kinematics (e.g., Davies et al. 2001). A first list of elliptical, lenticular, and spiral galaxies was composed for which SAURON can measure the stellar kinematics. This led to the following constraints: declination $6^\circ \leq \delta \leq 64^\circ$ (to limit the zenith distance and therefore the instrumental flexure), systemic velocity $V_{\text{sys}} \leq 3000$ km s$^{-1}$ (to ensure that all the lines of interest are in the spectral band), and absolute magnitude $M_B \leq -18$ (so that velocity dispersion $\sigma \geq 75$ km s$^{-1}$ and velocity dispersions can be measured). These objects were further restricted to avoid crowded fields and large Galactic extinctions. All parameters except $M_B$ were taken from the Lyon/Meudon Extragalactic Database (LEDA; see Paturel et al. 1989) and checked for consistency with the RC3 catalogue (de Vaucouleurs et al. 1991). Absolute magnitudes were derived following the prescription in LEDA, using the listed heliocentric velocities and apparent magnitudes and $H_0 = 75$ km s$^{-1}$, and the correction to the Local Group centroid of Yahil, Tammann & Sandage (1977). For galaxies in the Virgo cluster, the Coma I cloud and the Leo I group, which we refer to as cluster galaxies, we adopted common distances based on the mean heliocentric velocity of each group, taken from Mould et al. (1993). The distances derived, 16.3, 13.7 and
10.7 Mpc, respectively, are in good agreement with those derived from other measurements (e.g., Ferrarese et al. 2000). For galaxies outside these three associations, which we refer to as field galaxies, we used individual distances (see de Zeeuw et al. 2002; section 2.1 for distance references). A further selection was done since we required our final sample to be equally divided between elliptical, lenticular, spiral, field and cluster galaxies (12 galaxies in each sub-category). The final set of galaxies covers a large range of global and nuclear properties, the details of which are presented in de Zeeuw et al. (2002). For the rest of this thesis, we focus on the spiral sub-sample, and for more information about the rest of the sample, the reader is referred to de Zeeuw et al. (2002).

We observed the 24 spiral galaxies during 6 of 8 runs which were allocated for SAURON. Detailed specifications for the data, reduction, and data preparation procedures can be found in Emsellem et al. (2004). Basic properties of all galaxies are presented in Tab. 3.1. We used the Low Resolution (LR) mode which implies a field-of-view size of $41'' \times 33''$ with a spatial resolution of $0.94''$ per element. The spectral domain and spectral resolution of the data are $[4820 - 5280]$ Å and 3.6 Å spectral resolution (corresponding to an instrumental dispersion of 108 km s$^{-1}$) respectively. This spectral range contains many useful features, and in particular we make use of the Mg$b$ 5167Å, 5173Å, and 5184Å, and Fe 5270Å absorption lines, H$\beta$ 4861Å, and the [O iii] 4959Å, 5007Å, and [N i] 5198Å, 5200Å emission-lines.

For each pointing we obtained 4 exposures of 1800 s. We also observed standard stars to be used for accurate velocity, flux, and line strength calibration of our observed galaxy. Wavelength calibration was done using arc line exposures taken before and after target exposure. Standard reduction procedure includes bias subtraction, overscan correction, dark current subtraction, spectra extraction, wavelength calibration, flat field correction in the spectral direction, cosmic ray rejection, sky subtraction, and flux calibration. These steps were performed using the software package XSAURON, and for each lens, we obtained a calibrated spectrum. Dithering of our 4 exposures resulted in resampling of the data to a common spatial scale of $0.8'' \times 0.8''$ per pixel. For the current study, we were forced to remove two of the galaxies: NGC 4425 and NGC 6501, since we were not able to detect any gas emission-lines.

### 3.3.1 Stellar Kinematics

When observing unresolved external galaxies, the radial velocity of the individual stars is different, leading to a Doppler shift of the spectrum of each individual star. The net effect on the observed galaxy spectrum at every position on the sky becomes then a broadening and an overall shift of the stellar absorption lines. These effects

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$^{1}$The XSAURON software is an adaptation for the SAURON instrument of the public XOASIS software (http://www.ing.iac.es/Astronomy/instruments/oasis/). The software has been developed at the CRAL, Lyon.
Table 3.1: Characteristics of the early-type spiral galaxies in the SAURON sample. All values are imported from the RC3 catalogue.

<table>
<thead>
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<th>Object</th>
<th>Type</th>
<th>$V_{sys}$</th>
<th>$D_{25}$</th>
<th>$R_{25}$</th>
<th>$B_T$</th>
<th>HST</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
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<td>Sa</td>
<td>1545</td>
<td>1.37</td>
<td>0.32</td>
<td>12.90</td>
<td>-</td>
<td>HII/Sey2</td>
</tr>
<tr>
<td>NGC2273</td>
<td>SB(r)a</td>
<td>1871</td>
<td>1.51</td>
<td>0.12</td>
<td>12.55</td>
<td>N/W</td>
<td>Sey2</td>
</tr>
<tr>
<td>NGC2844</td>
<td>Sa</td>
<td>1486</td>
<td>1.19</td>
<td>0.31</td>
<td>13.75</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NGC3623</td>
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Notes: (1) NGC number and location. Field galaxies are indicated by f, and cluster galaxies are indicated by c. (2) Morphological type. (3) Systemic Velocity in km s$^{-1}$. (4) Mean decimal logarithm of the apparent major isophotal diameter measured at or reduced to surface brightness level $\mu_B = 25.0$ B/mag$^2$. (5) Mean decimal logarithm of the ratio of the major isophotal diameter, $D_{25}$, to the minor isophotal diameter, $D_{25}$. (6) Total B magnitude. (7) HST data availability (N=NICMOS, S=STIS, W=WFPC2) (8) Activity and/or HII content classification from the NASA/IPAC Extragalactic Database (NED).

are quantified by assuming that all the stellar spectra are identical, and hence one assumes that the observed spectrum is a “stellar template” convolved with the LOSVD. In order to measure the relatively small contribution of the random motions to the total broadening of the LOSVD as well as measuring the line-of-sight kinematics, we must first characterise the exact shape of the LOSVD. Conventionally, it has been assumed that the LOSVD is Gaussian (Bender, Saglia & Gerhard 1994), characterised by a mean velocity, a velocity dispersion, and a line-strength parameter. This
assumption gives convenient fits for most observed galaxy spectra. Various ways to measure velocity and velocity dispersion include: Fourier Quotient (Sargent et al. 1977); Cross-Correlation Method (Simkin 1974; Tonry & Davies 1979); Fourier Correlation Quotient (Bender 1990), and Unresolved Gaussian Decomposition (Kuijken & Merrifield 1993). However, there is no theoretical reason why the LOSVD of galaxies should assume a Gaussian shape. Several models of galaxies are able to produce non-Gaussian LOSVDs. Kuijken & Merrifield (1993) explained an asymmetry in the absorption feature to be due to superposition of a low dispersion rotating disk and a high dispersion and more slowly rotating bulge. Furthermore, superposition of different components, and/or a radially anisotropic velocity distribution can cause non-Gaussian LOSVDs (e.g., Franx & Illingworth 1988).

We derive the stellar kinematics by using a technique which relies on expanding the LOSVD $F(v_{\text{los}})$ as a Gauss-Hermite series (van der Marel & Franx 1993; Gerhard 1993). Accordingly:

$$F(v_{\text{los}}) \sim \left(\frac{\gamma G(w)}{\sigma}\right) \cdot \left(1 + \sum_{i=3}^{n} h_i H_i(w)\right),$$

(3.1)

where $w = \frac{V_{\text{los}} - V}{\sigma}$. The parameters $\gamma$, $V$, and $\sigma$ are the line strength factor, the mean velocity and the velocity dispersion. The $G(w)$ is the standard Gaussian, the $H_i(w)$ are the Hermite polynomials, and the Hermite coefficients ($h_i$) describe deviations from gaussianity. Throughout this chapter, we focus on the mean velocity and velocity dispersion terms of the stellar kinematic maps. In some cases, we are also able to make use of the third and fourth Hermite terms. The $h_3$ measures skewness of the LOSVD, and the $h_4$ is a measure of the kurtosis. Roughly speaking, the skewness measures the asymmetry, and the kurtosis is the degree of peakedness.

Using the Gauss-Hermite expansion, we fit the LOSVD in real pixel space. In pixel space, it is easier to exclude gas emission-lines or bad pixels from the fit. We make use of a large library of high resolution observed and model spectra (Jones 1997; Vazdekis 1999) to find the best-matching template spectrum to the galaxy spectrum within each spatial element, which we use to fit the stellar kinematics. When the stellar absorption lines are not prominent, the shape of the LOSVD cannot be determined to sufficient accuracy to allow the higher terms to be measured. Accordingly, the parameters ($V$, $\sigma$, $h_3$, $h_4$) are fitted simultaneously, with an adjustable penalty term added to the $\chi^2$ to bias the solution towards a Gaussian shape when the higher order terms ($h_3$ and $h_4$) are unconstrained. This penalised fitting method was developed by Cappellari & Emsellem (2004). These authors showed that the method guarantees a balanced fit of the data and avoids excessive roughness or rapid variation. We convolve the best-matching template spectrum with the derived LOSVD, and obtain the best-fit stellar contribution to the spectra. Subtraction of the stellar contribution results in emission-line spectra, which we then use to derive the emission-line
distribution and kinematics (see Fig. 3.8). After deriving the gas kinematics (see section 3.3.2), we iterate this step once again, this time using the best-matching template spectrum to derive the stellar kinematics. This step helps to remove template mismatch effects.

3.3.2 Gas Kinematics

The wavelength range of SAURON spectra allows the observation of three main emission lines in nearby objects, namely H$\beta$, [O III], and [N II]. The full use of these gas emission-lines to derive the physical properties of galaxies is covered by a vast literature. Here, we mainly focus on the [O III] doublet at 4959Å, and 5007Å, which has an intrinsic 1:3.01 ratio and is mainly powered by collisional de-excitation. The [O III] lines are also generally assumed to be generated by the narrow-line emission from an AGN (e.g., Kauffmann et al. 2003). The spatially resolved gas distribution and kinematics are derived by fitting single Gaussians\(^\ddagger\) to the gas emission-lines (e.g., Véron et al. 1980). The shift and the equivalent width of the Gaussian provide the mean systemic velocity and the mean velocity dispersion of the gaseous component, which we use to measure masses, discriminate between regular, irregular, and non-equilibrium systems. The derived distribution maps give information about the equilibrium of the systems, and velocity and velocity dispersion maps display the regularity of the motions. In some cases one might argue that multiple Gaussians are better suited (see chapter 5 of this thesis), but for this study, we have derived the gas kinematics and distribution in an automated procedure (see Fig. 3.8 for an illustration of how different features in a spectrum are used for deriving the kinematics).

The Gauss-Hermite expansion of the stellar LOSVD only provides consistent higher moments when the signal-to-noise $S/N$ is higher than a threshold (Emsellem et al. 2004). To increase the $S/N$ per pixel, we have applied the spatial Voronoi binning technique developed by Cappellari & Copin (2003) which allows creation of compact bins with a given minimum $S/N$ per pixel. Accordingly, the derived stellar kinematics makes use of spectra which have been binned to $S/N$ of at least 60 per element. Inspection of the stellar kinematics maps shows that some of the Voronoi bins are very large. The binning threshold is necessary for the derivation of the stellar kinematics, whereas the same binning levels are not needed for the derivation of the emission-line kinematics. Using the stellar binning scheme for the gas kinematic maps may imply that we lose spatial information, since in some cases, the bins are large. This was taken care of by first assigning the stellar kinematics information ($V, \sigma, h_3, h_4$) for each Voronoi bin to all the pixels that are included in the bin. Once again the best-matching combination of the stellar templates to each “original and unbinned” spectrum is found, followed by fitting the gas emission-lines.

\(^\ddagger\)At high densities, collisional broadening becomes important and the resulting line profile is better characterised by the Voigt function (Audley 1997).
Figure 3.8: This figure illustrates the steps of deriving the kinematics. All spectra are given on an arbitrary flux scale, and shifted in the vertical direction for clarity. (a) The galaxy spectrum, as delivered by SAURON. (b) Best-fit to the underlying stellar component (Optimal Template Fit). (c) Pure emission-line spectrum (a – b), which we use to derive the gas kinematics. (d) Emission-free galaxy spectrum (a – fits to the emission-lines), which we use to derive the emission-free stellar kinematics.

At this stage, different emission-lines can be fitted independently, and also individual emission-lines can be investigated. We found that not all the emission-line kinematic values should be trusted, and decided to trim the gas maps, in order to remove noisy and unreliable regions. The trimming was done using the gas amplitude-over-noise ($A/N$), which we define to be the average of the tree maximum emission-line values divided by the standard deviation of the spectra which do not exhibit any emission. Testing a series of $A/N$, we found that all spectra with $A/N > 4$ provide reliable gas kinematics. To conclude, none of the gas maps presented in this thesis have been binned and only include spectra with $A/N > 4$.

3.4 Gas Velocity Field Analysis

The main goal of the study in this paper is to detect and quantify the non-circular signatures in our observed velocity fields. The first step of our analysis is based on
the assumption that the observed gas velocity field lies in an infinitesimally thin, and predominantly rotating, circular disk. Then the line-of-sight velocity (V_{los}) is given by

\[ V_{los}(R) = V_{sys} + V_{rot}(R) \cos(\psi) \sin i, \]  \tag{3.2}

where \( V_{sys} \) is the mean systemic velocity, \( V_{rot} \) is the circular velocity, \((R, \psi)\) are polar coordinates in the plane of the galaxy, and \( i \) is the inclination at which the disk is projected on the sky. When axisymmetric radial velocities are present, an additional term is added to Eq. (3.2). By convention, position angles are measured counter clockwise from the receding side of the galaxy major-axis.

Considering purely circular disks, some properties for \( V_{los} \) are useful to point out. In the case of constant density (possible for observations of centres of galaxies), \( V_{rot} \) is given by \( V_{rot}(R) = \Omega R \), for which \( V_{los}(R) = \Omega R \cos \psi \sin i \). The constant velocity contours are accordingly parallel to the minor-axis. In the case of a flat rotation curve, we define \( V_{rot} = \zeta \), for which \( V_{los}(R) = \zeta \cos(\psi) \sin i \). For this case, the isovelocity contours are lines going diagonally through the centre (see Fig. 3.9a).

One can construct more complex velocity fields by adding multiple disks with different sizes, circular velocities, and orientations (see Fig. 3.9b).

### 3.4.1 Exponential Disks

The above models are not entirely adequate for studying more realistic disks (for these, see chapter 2.6 in Binney & Tremaine 1987). Observationally, disks show an exponential light distribution which can be generated by the potential

\[ \Phi(R, z) = -2\pi G \Sigma_0 r_d^2 \int_{0}^{\infty} \frac{J_0(kR) e^{-k|z|}}{[1 + (kr_d)^2]^{3/2}} \, dk, \]  \tag{3.3}

where \((R, z)\) are cylindrical coordinates, \( G \) is the gravitational constant, \( \Sigma_0 \) is the central surface brightness, \( r_d \) is the scale length of the disk, and \( J_0 \) is the cylindrical Bessel function of order zero. It was demonstrated by Freeman (1970) that when the disk is infinitesimally thin \((z \to 0)\) and in centrifugal equilibrium, \( V_{rot} \) is given by

\[ R \frac{\partial \Phi}{\partial R} = V_{rot}^2(R) = 4\pi G \Sigma_0 r_d F^2 [I_0(F)K_0(F) - I_1(F)K_1(F)], \]  \tag{3.4}

where \( F = \frac{R}{r_d} \), \( I_n \) and \( K_n \) are Bessel functions of the first and second kind. Rotation curves of this form rise quickly, and decrease after about two scale lengths. A velocity field of such a disk is presented in Fig. 3.9, where the constant velocity curves form a spider diagram.

### 3.4.2 Perturbed Velocity Fields

Commonly observed velocity fields exhibit more complex features than those presented in Fig. 3.9. Non-axisymmetric perturbations as well as non-gravitational motions affect the observed velocity field. In the case of presence of an axisymmetric
radial component, a projected radial term \( V_{\text{rad}} \) is added to Eq. (3.2), and the line-of-sight velocity is then given by

\[
V_{\text{los}}(R) = V_{\text{sys}} + V_{\text{rot}}(R) \cos(\psi) \sin i + V_{\text{rad}}(R) \sin(\psi) \sin i.
\] (3.5)

It has been demonstrated by Franx, van Gorkom & de Zeeuw (1994) and Schoenmakers, Franx & de Zeeuw (1997) that an observed velocity field can be decomposed into a harmonic series, the coefficients of which provide quantitative information about non-axisymmetric structures:

\[
V_{\text{los}}(R) = c_0 + \sum_{n=1}^{k} [c_n \cos(n\phi) + s_n \sin(n\phi)] \sin i,
\] (3.6)
where \( c_0 \) is the systemic velocity, \( c_1 \) is the circular velocity, and \( s_1 \) corresponds to the axisymmetric radial velocity, and \( \phi \) is an angle measured in the plane of the orbit and is zero at the line of nodes. This formalism has been used by Wong, Blitz & Bosma (2004) to model the effects of gravitational perturbations by bars and spiral arms on an axisymmetric velocity field. Assuming positive pattern speed \( \Omega_p \) and a weak bar (\( \Phi_m \ll 1 \)), the potential may be divided into zeroth- and first-order parts (Binney & Tremaine 1987, p.146ff). Note that the zeroth-order terms are much larger than the first order terms indicating that the particles are in nearly circular orbits. The analytic solution to this problem is obtained by simulating a frictional force, that is proportional to the radial velocity perturbation, by introducing a damping term \( \lambda \) into the equations of motion (Lindblad & Lindblad 1994; Wada 1994; Byrd, Ousley, & dalla Piazza 1998). Considering an axisymmetric rotating potential, the potential \( \Phi \) is given by

\[
\Phi(R, \theta) = \Phi_0(R) + \Phi_m(R) \cos[m(\theta - \Omega_p t)],
\]

where \( \Phi_0 \) is the axisymmetric potential, \( \Omega_p \) is the angular speed of the rotating potential, and \( m \) is the harmonic number of the distortion. For the case of \( m = 2 \) the potential is barred. The equations of motion are written as

\[
-\frac{\partial \Phi}{\partial R} = \ddot{R} + 2\lambda \dot{R} + (\dot{\phi} + \Omega_p)^2 R
\]

\[
-\frac{\partial \Phi}{\partial \phi} = \ddot{\phi} + 2(\dot{\phi} + \Omega_p) \dot{R}
\]

which are expressed in terms of polar coordinates \((R, \phi)\), and \( \phi = \theta - \Omega_p t \) is the azimuthal angle in the rotating frame which is zero at the long axis of the potential. The bar damping term is \( \lambda \). The effect of \( \lambda \) on the velocity field is illustrated in Fig. 3.10. For the simplest case, when the bar damping is ignored, applying the epicyclic approximation for centrifugal equilibrium in a barred potential, Binney & Tremaine (1987) derive the equation of motion of the harmonic oscillator of natural frequency \( \kappa_0 \) that is driven at frequency \( m(\Omega_0 - \Omega_p) \) as

\[
\ddot{R}_1 + \kappa_0^2 R_1 = \left[ \frac{d\Phi_m}{dR} + \frac{2\Omega \Phi_m}{R(\Omega - \Omega_p)} \right]_{R_0} \cos[m(\Omega_0 - \Omega_p)t],
\]

where \( \Omega_0 \equiv \Omega(R_0) \) and \( R(t) = R_0 + R_1(t) \). When the pattern speed is non-zero, the stable orbits of this collisionless weak bar model change orientation when crossing the resonances. Many of the resulting orbits intersect each other and are hence not accessible to the gas component, since only one velocity is permitted for a fluid at a given spatial location. The gaseous orbits are expected to turn gradually between resonances. Eq. (3.9) is then written as

\[
\ddot{R}_1 + 2\lambda \dot{R}_1 + \kappa_0^2 R_1 = -\left[ \frac{d\Phi_m}{dR} + \frac{2\Omega \Phi_m}{R(\Omega - \Omega_p)} \right]_{R_0} \cos[m(\Omega_0 - \Omega_p)t].
\]
Adopting the harmonic decomposition of the $V_{los}$, for the solutions for $(R, \phi, v_{rot}, \mathrm{and} \, v_{\text{rad}})$ in the rest frame of the bar, as given by Sakamoto et al. (1999) one obtains

\begin{equation}
\begin{align*}
    c_0 &= V_{\text{sys}} \\
    c_1 &= v^* \left[ 1 - \frac{1}{4} \left( 1 - 2\omega_p \right) A \cos(2\theta_{\text{obs}} + \delta_0) + (1 - \omega_p) B \cos(2\theta_{\text{obs}} + \beta_0) \right], \\
    s_1 &= v^* \left[ 1 - \frac{1}{4} \left( 1 - 2\omega_p \right) A \sin(2\theta_{\text{obs}} + \delta_0) + (1 - \omega_p) B \sin(2\theta_{\text{obs}} + \beta_0) \right], \\
    c_3 &= -v^* \left[ (2\omega_p - 3) A \cos(2\theta_{\text{obs}} + \delta_0) + (1 - \omega_p) B \cos(2\theta_{\text{obs}} + \beta_0) \right], \\
    s_3 &= v^* \left[ (2\omega_p - 3) A \sin(2\theta_{\text{obs}} + \delta_0) + (1 - \omega_p) B \sin(2\theta_{\text{obs}} + \beta_0) \right],
\end{align*}
\end{equation}

where $v^* \equiv V_{\text{rot}} \sin i$, the viewing angle is $\theta_{\text{obs}}$ and the orbit parameters $(A, B, \delta_0, \beta_0)$ are given by

\begin{equation}
\begin{align*}
    A &= -\frac{\varepsilon}{(1 - \omega_p) \sqrt{(1 - 4\omega_p + 2\omega_p^2)^2 + 4\varepsilon^2 (1 - \omega_p)^2}}, \\
    B &= -\sqrt{\left( \frac{2A}{1 - \omega_p} + \frac{\varepsilon}{(1 - \omega_p)^2} \right)^2 + \frac{4\varepsilon}{(1 - \omega_p)^2} (\cos \delta_0 - 1)}, \\
    \tan \delta_0 &= \frac{2\delta_0 (1 - \omega_p)}{1 - 4\omega_p + 2\omega_p^2}, \\
    \tan \beta_0 &= \frac{\sin \delta_0}{\cos \delta_0 + \frac{4\omega_p}{2 + \sqrt{4(1 - \omega_p)^2}}},
\end{align*}
\end{equation}

where $\varepsilon$ is the potential ellipticity and $\omega_p \equiv \frac{\Omega_p}{\Omega_0}$.

The observable effect of this type of perturbation on a single rotating disk velocity field, is illustrated in Fig. 3.11. Using a similar approach, the harmonic terms for a warped potential or a spiral perturbation were derived by Swaters et al. (1999) and Wong, Blitz & Bosma (2004). We refer the reader to these references for the detailed derivation of the corresponding formulae. In Fig. 3.12, we present the effects of some example spiral perturbations on an exponential disk. Our illustrations demonstrate that a variety of observed features may be created by bars and spiral arms. The observational effects on the velocity fields depend on the physical and geometrical characteristics of the bar or the spiral arms, and clearly also depend on the viewing angle. Investigating the harmonic terms as a function of radius illustrates the potential of this technique to quantify the relative effect of perturbations in an observed velocity field. In Figures 3.11 & 3.12, to build the models, we have matched the sampling of the SAURON observations in order to introduce the reader to the maps in the following chapters. In consecutive chapters of this thesis, we demonstrate the full application of this method, and how this can be used to analyse observed velocity fields.
Figure 3.10: The effect of $\lambda$ on an observed velocity field. In all cases, $\epsilon = 0.1$, and a viewing angle of $-50^\circ$ is adopted. The circle indicates the location of the CR of the bar.

3.5 SAURON Data Analysis

We use the methods of sections 3.3.1 and 3.3.2 to derive the stellar and gaseous kinematics for the SAURON spiral sample. We focus on the gas velocity fields, to which we first fit an exponential disk and obtain, to a first order, the disk parameters of Eq. 3.4. In rotationally supported systems, the orbits of gas and stars in the disk are usually deviating only slightly from circular orbits. Investigating the residual field (Data - Disk Model), we find that in almost all our galaxies the residuals exhibit systematic features. These features in the residual fields are indicative of perturbation effects (or external effects) superimposed on the observed rotating disks. We pursue a study of these features by applying the tilted-ring decomposition of the gas velocity field (Begeman 1987; see also chapter 4 of this thesis).
According to this method, we divide each field into concentric rings within which we fit the $V_{\text{sys}}$, PA, and rotation speed. We assume that our measurements refer to positions on a single inclined disk, and that the photometric centre coincides with the dynamical centre. Fixing the inclination to the RC3 value and holding the central coordinates fixed, we fit $V_{\text{sys}}$, and PA for each ring, and obtain a radial profile for these parameters. We fix the systemic velocity to the bi-weight mean value of the fitted $V_{\text{sys}}$ for all the rings and fit the PA, followed by fixing this parameter. At this stage we fit the circular velocity component, subtraction of which leaves us with the non-circular velocity components.

Using this method with the harmonic decomposition formalism of Eq. 3.6, for each ring we derive the corresponding set of harmonic parameters by least-squares-fitting. As a result, for each galaxy, we derive PA, $V_{\text{sys}}$, $V_{\text{rot}}$, $V_{\text{rad}}$, and the second
Figure 3.12: (a) Toy models for illustrating the effects of a spiral perturbation and the corresponding harmonic terms $s_1$, $s_3$, and $c_3$ as a function of $\omega_p = \Omega_p/\Omega_0$. The bottom right panels are the normalised $s_3$ versus $s_1$ for this perturbation. (a) A “parent” exponential disk and the effect of a spiral perturbation. Spiral pitch angle is 15°, and the wave amplitude is $0.2V_{\text{rot}}$. (b) Here, the spiral pitch angle is 35°, and the wave amplitude is $0.2V_{\text{rot}}$.

and third harmonic parameters as a function of galactocentric radius. All maps are presented in Fig. 3.16 and the tilted-ring results are presented in Fig. 3.17.

3.5.1 Errors and Tilted Rings

Our data and the applied analysis method are subject to many different sources of errors. As for the data, since we are dealing with extracted gas velocity fields of which the errors are affected by subtraction of the stellar continuum, error estimation becomes a very difficult task. The spectra contain some Poisson errors, and other sources of errors are introduced when deriving the stellar kinematics. We then apply the optimal template fitting to get the underlying stellar contribution to our spectra, and finally derive the gas kinematics by fitting a single Gaussian to the emission-
lines. For the harmonic decomposition and derivation of the kinematic parameters, we tackle the error estimation problem in a rigorous way. We use the Bootstrap Monte-Carlo method (using 1000 iterations), and obtain errors of the non-linearly fitted parameters \( \text{PA} \) and \( V_{\text{sys}} \) from the bi-weight standard deviation of our simulations. Since this method does not assume any specific error distribution, it clearly overestimates the errors when deriving the harmonic parameters. We thus estimate the errors for the linearly fitted parameters \( V_{\text{rot}} \) and the higher terms by using the standard deviation of the fits.

When sectioning the field into concentric rings, the radial extent of each ring is a free parameter which has to be pre-determined. For a range of possible ring radii, we have examined the fitted velocity information and have found that the determination of the radial thickness of the rings becomes a trade-off between smoothness of the fitted velocity field, and the magnitude of the errors. We have found that choosing rings with two pixel wide thickness gives optimal derivation of the harmonic parameters for the central 10-15″ of most of the maps. In all the cases, given that the gas distribution becomes patchy in the outer parts of the observed field, the number of data points go down. We have used one thick ring for the outer parts. With the exception of NGC 5475 and NGC 5636 for which the gas fields are very small, the outer radius is \( R = 13-15″ \).

3.5.2 Notes on Individual Galaxies

**NGC 1056** is a Seyfert galaxy that hosts a large bulge, and has an extremely extended envelope. The SAURON stellar distribution is smooth, with kinematics displaying large-scale rotation features with some indication of a small scale kinematically decoupled component. The stellar velocity dispersion increases towards the centre, but decreases in the central radius \( R = 3″ \), indicating a disk-like stellar component, and the fourth moment, \( h_4 \), displays a peak at the same spatial location as the velocity dispersion. The [O III] gas component has a patchy distribution, with a prominent rotating behaviour. The gas velocity dispersion is almost constant (\( \sim 100 \text{ km s}^{-1} \)) throughout the field. On the east side, probably due to dust, the isovelocity contours are more open than those on the west. This feature also appears on the large-scale \( \text{H} \) velocity field from E. Noordermeer (private communication). The large-scale \( \text{H} \) features are indicative of a warp seen edge-on. Our exponential disk fit yields a scale length of the large disk of 6″ and its residual field displays a clear three-fold symmetry which could be indicative of an \( m = 2 \) potential perturbation. At the centre, we detect radial motions up to 0.8\( v^* \), which smoothly decrease to zero at \( R = 7″ \). Over the same radii, we also detect a significant \( c_2 \), which goes down to zero. The \( s_3 \) vs. \( s_1 \) curve lies on a negative slope, indicating elliptical streaming in this galaxy (cf. Fig. 3.11). This is indicative of a bar.

**NGC 2273** is a double barred and ringed Seyfert 2 galaxy, with \( \text{H} \) regions at the
end of the bar (González Delgado et al. 1997). The primary bar is oriented at 115° and ends at \( R \approx 55'' \). The CO rich secondary bar, with a major-axis \( R \approx 4'' \) is almost perpendicular to the primary bar. This galaxy hosts dust in a \( \sim 40'' \) ring, and has another central ring at \( R \approx 10'' \) aligned at \( \sim 45° \) (Schonmer et al. 1988; van Driel & Buta 1991; Golev et al. 1995; Ferruit, Wilson & Mulchaey 2000; Petitpas & Wilson 2002). The large-scale bar indicates inflow (Combes 1994), but the CO velocity field does not show characteristic ‘S’-shaped contours. Numerical models have predicted that this ring indicates the location of the ILR of the primary bar (Shaw et al. 1993).

In our maps, we easily detect the prominent stellar bar in the photometry. The stellar velocity field displays a rotating component, and the velocity dispersion increases smoothly towards the centre. The third and fourth moments display no significant behaviour. The gaseous component is distributed smoothly with no clear signatures of the primary bar morphology, but with some indication of the secondary bar. The velocity dispersion of the gas is on average higher than that of the stellar component, and it displays a gradient perpendicular to the primary bar. The gas velocity field displays prominent rotation, with a strong kinematic twist of \( \sim 120° \) indicative of strong streaming in the central \( R = 7'' \). This kinematic behaviour corresponds to the ring at \( R \approx 10'' \) caused by the large-scale bar or inner spiral arms. At this radius, the disk residual field displays large residuals. The PA twist is so large that fixing the PA to the outer values cannot deliver reliable harmonic fitting in the central 7''. Inspection of the harmonic terms indicate significant radial inflow \( s_1 \) terms in the centre. Although this can be driven by the strongly barred potential, the \( s_3 \) vs. \( s_1 \) curve suggests that the radial flow is axisymmetric.

**NGC 2844** hosts a nuclear ring and dusty arms throughout the disk, and has a small central bulge. Brightest in a group with NGC 2852 and NGC 2853, this galaxy has a very small bright nucleus. Baes et al. (2003) estimate the circular velocity and bulge velocity dispersion to be 171 ± 10 km s\(^{-1}\) and 113 ± 12 km s\(^{-1}\), with a nuclear black hole mass of \( 10^{7.13\pm0.21} M_\odot \).

The **SAURON** observations show clear rotation for the stellar as well as the gaseous component, with a slowly rising gas rotation curve outside the central 2''. The stellar velocity field exhibits an ‘S’-shaped zero-velocity curve indicating the presence of gas streaming. Along the bar, the velocity dispersion exhibits a plateau and the \( h_3 \) term correlates with the line-of-sight velocity, which confirms the presence of the bar (Bureau & Athanassoula 2005). The central stellar velocity dispersion is \( \sim 100 \) km s\(^{-1}\), consistent with Héraudeau et al. (1999). The [O\,iii] gas displays a very patchy distribution and disk-like kinematics. Subtracting the best-fitted exponential fit from the data shows a three-fold symmetry, indicating the presence of an \( m = 2 \) mode. The harmonic terms are suggestive of some peak in the perturbation at \( R \approx 15'' \), but a more detailed look at the data reveals that this may be due to low signal-to-noise in the south-west part of the field. The \( s_3 \) vs. \( s_1 \) curve indicates elliptical streaming (cf.
Fig. 3.11).

**NGC 3623** is a barred Sa galaxy and a member of the Leo Triplet. While there are strong indications that the two other members of the triplet (NGC 3627 and NGC 3628) are interacting, NGC 3623 appears undisturbed (Chromey et al. 1998). It is one of the galaxies discussed by Hubble (1943) in his paper on the sense of rotation of spiral arms, to illustrate dust asymmetry as a diagnostic to determine the near side of a galaxy and therefore to determine the direction of opening of the spiral pattern. In NGC 3623, the bulge is small and the spiral pattern can be seen in the extinction maps and by the two main bright arms (Burbidge, Burbidge & Prendergast 1961). Most spectroscopic observations of NGC 3623 were concerned with emission-line ratios, to probe the ionisation mechanism of the gas and the nuclear activity (e.g., Bresolin, Kennicutt & Garnett 1999). Molecular gas is detected in the central 15′′, and within the central 1-2′′ there is a drop in the Hα emission, a rapid rise in the X-ray, and a dearth of neutral Hydrogen (Haynes, Giovanelli & Roberts 1979).

The main dust lane is easily visible in the SAURON reconstructed image. It appears as the dark band covering the bottom 25 % of the field. The velocity field shows a typical rotation pattern, but also reveals twists in the kinematic minor-axis and a gradient along the minor axis (minor-axis rotation). This is not unexpected, as NGC 3623 is barred. However, it is difficult to estimate how much of this structure is affected by the dust extinction. One feature which is certainly not due to dust is the central $R \approx 10''$ stellar disk, clearly visible as a flattening of the isovelocity contours in the centre of the galaxy, together with the anti-correlation of $h_3$ and velocity. In the centre, along the minor-axis, we detect a decrease of the stellar velocity dispersion. This is also consistent with a central disk. This profile shows higher values than those derived by Afanasiev & Sil’chenko (2004) but is consistent with minor-axis slit observations by Proctor (2002). Outside $R \approx 10''$, $h_3$ correlates with the velocity, confirming the dominance of the large-scale bar (Bureau & Athanassoula 2005). The gas has a patchy distribution with some hints of spiral arm configuration, and a highly twisted zero-velocity curve. Subtracting a disk model from the gas velocity field unveils a three-fold symmetry, which is also indicative of an $m = 2$ perturbation. This is confirmed by studying the $s_3$ vs. $s_1$ behaviour from the harmonic decomposition.

**NGC 4220** is highly inclined and forms a non-interacting pair with NGC 4218 at 15′. Our unsharp-masked stellar distribution map displays a prominent dust lane at a distance of 5″ north-east of the round and bright nucleus. The photometry reveals a clear boxy/peanut-shape bulge component. The stellar velocity field exhibits clear rotation, with some zero-velocity curve twist in the central few arcseconds. The stellar velocity dispersion and $h_4$ are both increasing toward the centre. The [O iii] gas distribution is very similar to that of the stars, although it is not detected in the outer parts of the SAURON field. The gas kinematic major-axis is oriented about 35° from that of the stellar kinematics, suggestive of a decoupled component in the inner
The gas velocity field displays prominent signatures of non-circular motions, the $s_3$ vs. $s_1$ curve (apart from the two outermost points) suggests elliptical streaming due to the spiral arms (cf. Fig. 3.12). We do not detect the bar in the photometry. In the central 10″, where the rotation curve is slowly rising, we derive large $s_1$ values with changing sign followed by a fall to zero. All other harmonic terms are consistent with zero.

NGC 4235 is a Seyfert 1 galaxy with old stellar populations (Jiménez-Benito 2000), and is in a non-interacting pair with NGC 4246 at 12′. It is nearly edge-on with strongly reddened (by the prominent dust in the spiral arms) nuclear emission and with optical emission-lines that extend along the major-axis (Abell, Eastmond & Ward 1978; Morris & Ward 1988; Colbert et al. 1996). The morphology of the extra-planar emission appears diffuse and bubble-like, especially towards the west.

Our observations for this galaxy display some prominent dust lanes reaching the central parts. The stellar kinematics displays a prominent outer disk-like component and a smaller rapidly rotating central component. We also find a central $\sigma$-drop and anti-correlating $h_3$ and $V$. The gas is found in an elongated shape, tracing the thin gaseous disk, with more complex kinematics than the stars. The gaseous component rotates faster than the stellar component and our measured central $\sigma$ is consistent with the previously measured value of 196±3 km s$^{-1}$ (Jiménez-Benito 2000). The PA profile delivered by the tilted-ring decomposition of the gas velocity field changes orientation by about 40°, and although the rotation is dominant, removing the best-fitted disk component reveals the presence of significant non-circular velocities (three-fold symmetry), especially in the inner 10″. The $s_3$ vs. $s_1$ graph displays a positive slope. This is not straightforward to interpret since the PA of the gas is so different from the stars.

NGC 4245 is a barred galaxy with a prominent inner ring at ∼ 30″, where the spiral arms originate from the ends of the bar. It appears that the arms join and form an outer ring. The SAURON observations show a smooth stellar distribution within the stellar bar and indication of a central disk in the inner $R = 5''$. This is confirmed by the stellar velocity field and the central $\sigma$-drop. The gaseous component is more concentrated south of the nucleus. Similar to NGC 4235, for this galaxy, the gas zero-velocity curve is not straight, and the residuals displays considerable non-circular velocities. The residual maps do not exhibit any symmetries with some indication of the presence of two spiral shape features. The PA twists by ∼ 40° in the central $R = 10''$, where we also detect strong radial flows. The overall behaviour of the harmonic terms together with the positive slope of the $s_3$ vs. $s_1$ indicate the dominant effect of the spiral arms (cf. Fig. 3.12).

NGC 4274 is a relatively gas poor barred galaxy, with two luminous inner arms and associated dust, tightly-wound large-scale spiral arms, and a very bright nucleus in a $D = 100''$ bar seen almost end-on (Braine et al. 1993; Laurikainen & Salo
The SAURON maps shows very prominent dust lanes and a prominent disk-like structure in the central $R = 10''$ in the velocity field, which is embedded in the large-scale rotating bar. At the location of the central disk, $h_3$ is anti-correlated with $V$, and $\sigma$ shows a local minimum. Outside this region, these two entities seem to correlate. The ionised-gas shows an elongated distribution and typical bar-like velocity field (‘S’-shaped zero-velocity curve). In the central $R = 7''$, the PA twists $\sim 20^\circ$ and remains almost constant throughout the rest of the field. $V_{\text{rot}}$ rises slowly and continuously throughout the SAURON field.

**NGC 4293** is a highly-inclined ($\sim 70^\circ$) galaxy with a large-scale bar of $D = 90''$ and ellipticity of 0.5 (Laurikainen & Salo 2002). Our stellar distribution map displays one dust lane passing through the nucleus and another dust lane about 7'' south of the centre. This galaxy seems to have a boxy/peanut-shape bulge. The stellar $\sigma$ and $h_4$ both increase homogeneously toward the centre. The gaseous component is distributed in an elongated and lopsided 5-10'' central structure with a kinematic major-axis about 35° from that of the stellar component. The gas velocity field is suggestive of a non-equilibrium system, or affected by a large amount of extinction in the central $\sim 10''$, or possibly there are some problems with the data. For these reasons, the harmonic decomposition does not provide meaningful results in the central parts of this galaxy. Although we apply the harmonic decomposition with great caution for the central regions, we find that the gas $V_{\text{rot}}$ stays at about 40 km s$^{-1}$ in the inner 5'', then decreases to half this value in the range 5-15'', followed by a rise to about 60 km s$^{-1}$ in the outer 15-22''. The gas $\sigma$ map is smoothly increasing toward the centre, reaching about 180 km s$^{-1}$ in the centre, about 50 km s$^{-1}$ larger than the central $\sigma$ of the stars. Subtracting the best-fit exponential disk from the gas velocity field unveils a prominent three-fold symmetry, which is consistent with the effect from an $m = 2$ perturbation, i.e., the bar. The $s_3$ vs. $s_1$ for the rings larger than $R = 10''$ curve also suggests the presence of the bar (cf. Fig. 3.11). Additionally to the large $s_1$ term in the centre and the elliptical streaming by the bar, we also derive significant $c_2$ values in the central 12''.

**NGC 4314** is characterised by a prominent $D = 140''$ bar, a smaller bar mis-aligned with respect to the primary bar by 5°, a somewhat elongated 15-20'' bulge, a nuclear star-forming ring at $R = 5''$, prominent inner spiral arms, and faint outer spiral arms (Benedict, Smith & Kenney 1996). Ellipticity and PA profile from Pérez-Ramírez et al. (2000) suggest a further nuclear ring of about 1-2''. The disk, the bulge, and the bar have comparable luminosities (Ann 1999). The pattern speed of the primary bar has been derived to be 33-72 km s$^{-1}$ kpc$^{-1}$ and the pattern speed of the nuclear bar is expected to be about 12 times that of the primary bar (García-Barreto et al. 1991; Benedict et al. 1996; Ann 2001). Radial inflow speeds of 20-90 km s$^{-1}$ in two spurs of molecular gas located just outside the 5'' star forming ring have been detected by García-Barreto et al. (1991), and is confirmed by our $s_1$ profile.
from the harmonic decomposition results. The colour of the nuclear ring is much bluer than that of the surrounding regions, including the nucleus (Benedict 1980; Wakamatsu & Nishida 1980). The blue colour is commonly ascribed to young stellar populations that may have formed from disk material driven towards the centre by the bar potential. SPH simulations by Ann (2001) suggest that, in this galaxy, the nuclear ring can be formed from gas inflow along the bar because of the moderate central concentration of the bulge in a strong barred potential.

Our maps have shown that, for NGC 4314, the kinematic and photometric PAs are aligned. The SAURON distribution of the stars as well as of the gas display the presence of the central spiral arms and the 5″ nuclear ring. At this radius, the stellar velocity dispersion displays a local maximum. This behaviour is not followed by the gaseous component. The velocity dispersion of the gas only displays a peak at the centre. We detect the effect of the large-scale bar on the gas velocity field in the form of prominent twist in the gas zero-velocity curve. Moreover, the negative slope of the $s_3$ vs. $s_1$ curve is consistent with that of a spiral (cf. Fig. 3.12).

NGC 4369 is almost face-on with an inclination of $\sim 12^\circ$ and displays very small rotational velocities ($\sim 40$ km s$^{-1}$). The DSS image for this galaxy is featureless, but there are two discrete H$\alpha$ regions around the galactic centre (Usui, Saito & Tomita 1998). The spiral pattern in NGC 4369 is not readily apparent in the high-surface-brightness central region.

The SAURON stellar distribution is suggestive of lopsidedness in the centre, and the velocity map displays rotation with a break at $R = 10''$. At this radius $\sigma$ is high but patchy. In general, all stellar kinematic maps display very patchy and non-symmetric structures possibly due to patchy distribution. At the ring at 10″, where stellar velocities are low, we detect an increase in the $h_3$ together with a decrease in the $h_4$. The gaseous component also follows a very patchy distribution, especially at the centre. Although rotation is dominant, the residual field shows no significant features after removing the harmonic fit. In the central $R = 7''$, we derive very low projected gas rotational velocities ($\sim 50$ km s$^{-1}$), which then rises very quickly to values $\sim 100$ km s$^{-1}$. The high $V_{rot}$ values suggest that this galaxy is not face-on, or that the gaseous disk lies in a different plane.

NGC 4383 is a bright Seyfert galaxy with a star-like, blue nucleus (Brosch et al. 1997). The stellar distribution shows some filaments, with extremely complex stellar kinematics. The velocity dispersion map displays an increase throughout the entire field toward the centre. The [O III] gas displays a somewhat more clear sign of rotation, with very slowly rising $V_{rot}$, and indication of a central component in the inner 5″. The stellar and gaseous $\sigma$ have opposite behaviour. Removing the best-fit exponential disk reveals a significant three-fold symmetry in the residual field. This symmetry is strangely, not fitted by the harmonic decomposition fit to the gas velocity field. The PA profile is almost flat throughout the field except from the central $R = 5''$, ...
where it exhibits a twist of $\sim 50^\circ$. The gas and stellar zero-velocity curves are not well defined.

**NGC 4405** is a galaxy with no prominent spiral structure in an elongated and rotating stellar distribution, with some evidence of central dust lanes. However, our unsharp-masked images reveal a $10''$ bar or disk-like morphology. The stellar velocity is rather regular and $\sigma$ decreases at the central parts, indicating the presence of a cold system. The gas is more elongated and is rotating consistently with an exponential disk with a large disk scale length of $\sim 35''$. The stars and gas have comparable line-of-sight velocities, with slowly increasing rotation curves, and almost flat $V_{\text{sys}}$, and PA profiles. The two components are aligned. The gas velocity harmonic terms are almost everywhere consistent with zero except for the $c_3$ at $R = 5''$, and do not indicate any prominent perturbation feature. The residuals are indeed small and featureless.

**NGC 4596** is a non-interacting strongly barred galaxy with a diffuse bulge and no spiral arms. The radius at which the bar ends is evident from the shoulders in its outer parts at $R \approx 55'' \approx 4.6$ kpc and at a PA of $73^\circ$ (Kent 1990). The bar pattern speed has been estimated to be 43-52 km s$^{-1}$ kpc$^{-1}$ consistent with a fast bar (Kent 1990; Gerressen, Kuijken & Merrifield). Given that this value is rather high and that bars rapidly decelerate by dynamical friction (Hernquist & Weinberg 1992), the bar pattern speed values for NGC 4596 suggests that the bar has just formed.

The **SAURON** stellar distribution is very smooth, with dominant rotating stellar kinematics. We detect a disk-like component in the inner $5''$ region, for which we find a strong anti-correlation with $h_3$ in an associated drop in $\sigma$. Comparing the stellar kinematic PA with the photometric PA, we find that the two values differ by $\sim 30^\circ$. The central velocity dispersion is $\sim 150$ km s$^{-1}$, increases by about 10 km s$^{-1}$ at $R = 5''$ and decreases again towards the outer parts. This is in good agreement with Kent (1990) and McElroy (1995). The gas is, like the stars, smoothly distributed and rotating with the same alignment. For this galaxy, we cannot clearly recognise an ‘S’-shaped zero-velocity curve, presumably because the outer parts of the observed field do not allow reliable gas detection, so the field only covers a small part of the large bar. Removing the best-fitted exponential disk or the harmonic decomposition do not enhance the bar, and not much can be seen in the harmonic terms. The most prominent features are the systematic variation of the PA, and the rotation curve peak at $R = 6''$.

**NGC 4698** is dusty and hosts a low-luminosity Seyfert nucleus with narrow emission-lines, tightly wound spiral arms, and an elliptical-like bulge which dominates the central parts of the galaxy with no evidence of recent star formation (Bertola et al. 1999). The stellar velocity curves along the major-axis of NGC 4698 is characterised by a plateau. The stars show no rotation in the centre, and towards large radii their rotation reaches a value of 200 km s$^{-1}$ (Sarzi et al. 2001). The $\frac{v_{\text{max}}}{\sigma} \approx 0.86$ is
consistent with an isotropically rotating bulge (Davies et al. 1983). Sarzi et al. (2001) argue that, in addition to the round bulge and a disk, the presence of a third luminous component in the central region is needed to explain the central velocity plateau. This may mean the presence of a kinematically decoupled core (see Mehlert et al. 1998, for a list of KDCs in ellipticals), suggesting that this galaxy has experienced a second event in its history. According to Sarzi et al., this galaxy hosts a central disk perpendicular to the main disk. The ionised-gas rotation curve, like that of the stars, display a central plateau (Bertola & Corsini 2000) and the two are misaligned by 20°.

In the SAURON stellar and gaseous velocity fields, although the stellar and gas velocity fields are regular on large scales, we detect the suggested KDC in the central $R = 5''$. The systemic velocity of the stars appears to be different to that of the gas by 30 km s$^{-1}$. The eastern part of the observed field exhibits a deficient gas content, which appears to be caused by a data reduction problem. This could also be the reason for the lopsided $\sigma$ maps and the systemic velocity difference. The spectra of this galaxy have to be re-examined before any further analysis, since on the east side the blue part of the spectra has an abnormally large slope. The exponential disk fit as well as the harmonic decomposition do not deliver much new information apart from very low rotation values in the central 5'', followed by a rapidly rising rotation curve. The low rotation amplitude is probably the effect of the KDC, and hence the PA should not be held fixed for the tilted-ring decomposition. The $s_3$ vs. $s_1$ curve for the radii outside the KDC mimics that of elliptical streaming (cf. Fig. 3.11).

NGC 4772 is a case of obvious counter-rotation of the ionised-gas with respect to the stars. It is an outlier of the Virgo cluster (Haynes et al. 2000). It is classified as a Seyfert 1.9 galaxy by Ho et al. (1997) and exhibits two concentric but distinct H I rings. The centre is H I poor and dominated by a flattened bulge ($B/D = 0.44$) surrounded farther out by a segmented ring (Haynes et al. 2000), with prominent dust lanes oriented parallel to the major-axis. Within the dust lane, there are also filaments tracing the spiral structure. The kinematical decoupling of the nuclear ionised-gas ($R < 5''$), observed along both the minor and the major axes, has been interpreted as the signature of a misaligned embedded gas bar, rather than as evidence of counter-rotation. The [O III] velocities rise rapidly up to 100 km s$^{-1}$ along the minor-axis in the inner $R = 5''$ and then decrease out to 15''. The minor-axis stellar velocities are very flat, perhaps indicating a misaligned disk or a bar. There is also an apparent decoupling on the gas emission along the major-axis (Quinn, Hernquist & Fullagar 1993).

Our SAURON observations clearly show the counter-rotation of the stars and the gas, and the gas rotates faster than the stars. The stellar velocity field displays a straight zero-velocity curve, which to a first approximation has a ~ 30° misalignment with the photometric minor-axis of the outer disk. The gas kinematic PA derived with the tilted-ring decomposition is about 95° from that of the outer disk photometric PA,
and about 135° from the apparent stellar kinematic PA. In the outer parts, however, the H\textsubscript{i} gas is again aligned with the stars (Haynes et al. 2000). Despite that, in our maps, the stars are smoothly distributed, in ordered disk-like rotation, and with a velocity dispersion rising uniformly towards the centre. The [O\textsc{iii}] gas lies along filaments, and the map resembles a bar with ansae. The gas distribution and kinematics are suggestive of two different components or significant radial motions. The tilted-ring decomposition shows a strongly varying $V_{\text{sys}}$, and a steeply rising $V_{\text{rot}}$. Within the central $R = 2''$, the rotation velocity of the gas reaches 150 km s$^{-1}$ and then drops to zero at $R = 25''$. Our derived gas rotation curve nevertheless is superior to previous long-slit derivations, since previously the exact alignment of the gas was not known. In the harmonic residual field, we find still some significant $m = 3$ residual features, indicating that the harmonic decomposition does not reproduce the observed velocity features.

**NGC 5448** is studied in detail in chapter 4 of this thesis.

**NGC 5475** is a relatively featureless nearly edge-on galaxy with a spherical bulge, a projected disk ellipticity of 0.68-0.71, and a bulge-to-disk ratio of 0.14 (Peletier & Balcells 1997; Andredakis, Peletier & Balcells 1995). This galaxy was found by Falcón-Barroso et al. (2003) to exhibit no minor-axis rotation, and an almost symmetrically decreasing minor-axis velocity dispersion profile.

In our observations, the stars are smoothly distributed, lying in a fairly fast rotating disk, with $h_3$ anti-correlating with the velocity. The velocity dispersion peaks toward the centre. This galaxy is deficient in gas in the outer parts of the SAURON field, but there is plenty in the inner parts. The central velocity dispersion value for the gas is about twice as high as that of the stars. In the central $R \approx 10''$, the gas kinematics appears to be misaligned and rotate slower than the stars ($\text{PA}_{\text{gas}} - \text{PA}_{\text{stars}} \approx 80°$). This behaviour is very similar to that in polar-ring galaxies where gas is elongated along the minor-axis (Whitmore 1991). The harmonic decomposition results in a peak of the rotation curve of 30 km s$^{-1}$, and the exponential disk model yields a scale length 1.9 (cf. $r_d = 2'2$ from Khosroshahi, Wadadekar & Kembhavi 2000). However, due to the small areal coverage of the gas, the derived harmonic terms do not reach very far out in galactocentric radius. Both photometric and kinematic major-axes are perpendicular to the outer parts.

**NGC 5636** is a barred galaxy in a non-interacting pair with NGC 5638 at 2'. Our observations display the $R \approx 25''$ stellar bar very clearly in the stellar distribution map, and its ends are marked by a ring structure. The stellar velocity field exhibits clear disk-like structure with almost flat velocity dispersion, $h_3$, and $h_4$, although badly resolved spectrally. The ionised-gas is only detected in the central 4'', so we are unable to comment meaningfully about it.

**NGC 5689** is an almost edge-on barred galaxy with a large regular bright bulge ($B/D = 0.93$) with a bulge Sérsic shape parameter $n = 5.9$ (Andredakis, Peletier &
and two prominent dust lanes cutting across and beyond the bulge. The bulge in this galaxy appears to be boxy/peanut-shaped. It is the brightest non-interacting member of a group with NGC 5682, NGC 5683, and NGC 5693. Falcón-Barroso et al. (2003) detected minor-axis rotation of order of 20 km s\(^{-1}\) in this galaxy which they related to the presence of inner components such as disks or bars.

Our stellar distribution map displays a dust lane 5\(''\) to the south of the nucleus, and the stellar velocity field shows prominent signatures of the stellar bar (curved velocity line) and an inner stellar disk with 10\(''\) radius. The large-scale bar, is also indicated by the positive correlation between \(h_3\) and the velocity outside 10\(''\) (Bureau & Athanassoula 2005), and the inner disk is indicated by the anti-correlation of \(h_3\) and the velocity inside the 10\(''\) radius, together with a dip in the velocity dispersion at the same location. The ionised-gas displays a thin disk-like distribution and a fast rotating kinematics, with a gradient in the velocity dispersion. The rotation curve rises to about 200 km s\(^{-1}\) at \(R = 7''\). The residual field exhibits a three-fold symmetry only at \(\sim 5''\) radius, but we have not been able to use the harmonic decomposition to connect this effect with a bar.

NGC 5953 is a distorted Seyfert 2 galaxy (Reshetnikov 1993) closely interacting with NGC 5954. The two are separated by a projected distance of 6 kpc and their interaction is believed to cause the presence of star forming regions in the two galaxies and in a bridge between them (Jenkins 1984). The bright core of NGC 5953 is embedded in a large halo that merges with a component that enveloping the pair. Both galaxies are experiencing a burst of star formation in the circumnuclear regions. In NGC 5953, most the emission is within the central \(R = 10''\) (\(\approx 1.3\) kpc). Long-slit data from González Delgado & Pérez (1996) show that in the circumnuclear region a starburst coexists with high-excitation gas ionised by the active nucleus. NGC 5953 has a confusing morphology, with emission-knots, a rotationally supported blue disk (Rampazzo et al. 1995), a ring of star formation at \(R = 4''\), and a bright and compact bulge (Reshetnikov 1993; Kodaira, Watanabe & Okamura 1986). Inside 5\(''\), where the knots are located, \((B - V) = 0.35\), rising rapidly to \(\sim 1.0\) toward the outskirts. The ellipticity outside \(R = 5''\) varies between 0.1 and 0.25, showing a tendency to increase in the outer parts indicating the presence of an outer disk. Reshetnikov (1993) also detected non-circular motions of up to 55 km s\(^{-1}\) at 10-12\(''\), but with no interpretation. In the south-west, the high excitation gas follows the rotation curve well, but in the north-east this gas is redshifted by about 40 km s\(^{-1}\) with respect to the low ionisation gas and its maximum velocity reaches a value of 240 km s\(^{-1}\), suggesting a dynamical mass of \(1.5 \times 10^{10} M_\odot\) for the central \(R = 9''\), and with \(M/L = 1.66\) (González Delgado & Pérez 1996).

Our data exhibit a smoothly distributed stellar component with large-scale rotation and a very slowly counter-rotating subcomponent in the central \(R = 5''\) for which
the $h_3$ is correlated with the velocity. In the centre, we also detect a gradient in the stellar $\sigma$ map, aligned with the kinematic major-axis. The $h_4$ parameter is uniformly decreasing toward the centre. The [O \text{iii}] gas displays a more patchy distribution and is more concentrated toward NGC 5954 to the north-east (consistent with González Delgado & Pérez 1996). The [O \text{iii}] velocity map shows a smooth PA twist of about 100°, indicative of significant non-circular motions, and the corresponding $\sigma$ map is uniformly increasing toward the centre, less so along the kinematic minor-axis. With this strong PA twist, the mean PA determination becomes somewhat difficult. It is, moreover, clear that one cannot simply use the stellar photometric PA for fitting the gaseous kinematics. This becomes even more evident when looking at the best-fit exponential disk. When fitting the inner $R = 10''$ only, the derived PA is perpendicular to that obtained when fitting the region outside 10''. This fact may also indicate the presence of two components which rotate perpendicular to each other. Fixing the PA also complicates the harmonic decomposition of the gas velocity field, since the harmonic decomposition leaves significant residuals when fixing PA. However, we are able to confirm the consistency of our fitted value for the $V_{\text{sys}} \approx 1984$ km s$^{-1}$ by comparing with values from the literature (see Tab. 4 in Reshetnikov 1993). Our current fit indicates a slow increase of the gas rotation curve to about 130 km s$^{-1}$ at $R = 7''$ (cf. 200-240 km s$^{-1}$ from Reshetnikov 1993 and González Delgado & Pérez 1996). For this chosen PA, $V_{\text{rot}}$ then decreases to about 20 km s$^{-1}$ at $R = 25''$ radius. At this radius the tilted-ring fit compensates the deficient rotational velocity by returning very large harmonic terms. The $s_3$ vs $s_1$ curve displays a positive slope, which is not predicted by any of Wong’s (2004) models. This is not surprising since this galaxy is clearly interacting with NGC 5954.

\textbf{NGC 7742} hosts a prominent blue face-on ring surrounding a bright nucleus. The ring appears to be detached from the central bulge. A set of faint and tightly wound multiple spiral arms begin on the ring and continue outwards. This type of galaxy is believed to be the result of a close encounter between a primary that has suffered an almost direct hit by a secondary component, one galaxy going closely through the centre of the other (Roberts et al. 1991; Pogge & Eskridge 1993; Wozniak et al. 1995). The ring-like structure in the gas appears as a tightly wound multi-arm spiral structure, indicative of nuclear (< 1 kpc) resonant rings (Buta & Combes 1996). The spirals can be followed in the HST images into the central arcsecond via the dust absorption features. If we assume they correspond to a trailing wave, then the near side is in the north-east quadrant.

The \textit{SAURON} maps extend slightly beyond the ring, and the stellar as well as the gaseous content of the ring is evident (de Zeeuw et al. 2002). The stellar $h_3$ roughly anti-correlates with the stellar velocity, suggesting disk-like kinematics. The overall stellar $\sigma$ is low, whereas it increases in the ring. The [O \text{iii}] gas is in counter-rotation with respect to the stars, and is well fitted with both the exponential disk fit as well
as the harmonic decomposition. The amplitude of the stellar velocities is modest, because the galaxy is seen close to face-on, but the zero velocity curve is well-defined, with a stellar kinematic axis at $\sim -40^\circ$. Comparing this value with the gas kinematic PA, the counter rotation is confirmed. $V_{\text{rot}}$ increases steeply to $\sim 350$ km s$^{-1}$ at $R = 6''$, followed by a decrease at the location of the ring ($\sim 14''$), followed by yet another increase at about $R = 20''$. The residual map exhibits a ring structure in the central $5''$, which suggests an $m = 1$ mode. This is confirmed by the strong and systematic variation of the $V_{\text{sys}}$ from the harmonic decomposition (cf. our study of NGC 5448 in chapter 4). We derive significant radial motions in the central $7''$, coexisting with significant $c_2$ values, and all other terms consistent with zero. At the position of the ring, where $V_{\text{rot}}$ is at its lowest value, we derive also the lowest values for $s_1$.

3.6 Preliminary Results

In the previous section, we have presented panoramic observations of a representative sample of 22 early-type spiral galaxies. Our data set is considerably larger than any previous kinematic data set in the central regions of nearby galaxies. Our large spectral range (as opposed to Fabry-Perot) and large field of view allow quantitative investigations of the stellar as well as gaseous kinematics and dynamics of these galaxies. These data present many interesting features, such as misalignment between stellar and gaseous kinematics, and photometry; kinematically decoupled or counter rotating components; cylindrical rotation or disk-like types of rotation; considerable deviations from pure circular rotation, e.g., streaming motions due to non-axisymmetric potentials.

3.6.1 Inner Disks

Disk-like rotation is prominent in all of the 22 spirals with the exception of NGC 4383 (see Tab. 3.2). The stellar kinematics for this galaxy are extremely complex and clearly requires a more detailed analysis. Apart from the prominent large-scale disk-like rotation, in $45(\pm 5)\%$ of the objects we detect inner disk-like components which are generally aligned with the outer disks. Such disks are recognised by a local peak+dip in the rotation curve together with a central dip in the velocity dispersion and an anti-correlating $h_3$.

3.6.2 Alignment of Angular Momentum of Gas and Stars

It is well illustrated in Fig. 3.13 that a majority of the sample spirals exhibits misaligned gaseous and stellar component. This is one of the kinematic signatures that

§Note that from the original sample of 24 spirals, NGC 4425 and NGC 6501 were removed because of lack of gas.
gas is in general not moving in circular orbits in the disk, or that the gas is not settled onto the galactic disk. In case of external origin of the gas, the nature of the orientation mostly depends on the initial angular momentum and mass of the accreted material (e.g., Whitmore et al. 1990, Binney 1992, Bertola & Corsini 1999). In this case the observed kinematics can be interpreted as due to accreted gas which rotates in a disk which is warped or inclined with respect to the stellar disk (e.g., Steinman-Cameron et al. 1992). Such a gas configuration is possible in barred galaxies (Emsellem & Arsenault 1997).

In Tab. 3.2, we present our derived values for the kinematic PAs of the gas compared with the photometric PAs for the stellar disk. To the kinematic PAs of the gas, we use the PA profiles from the tilted-ring decomposition of the gas velocity fields. For each galaxy, the average value of the derived PAs of all tilted-rings is then the kinematic PA of the gas. The stellar photometric PA is imported from the RC3 cata-

**Figure 3.13:** Distribution of $|\Delta PA|$ in early-type spiral galaxies. The white histograms are the distribution for the entire spiral sample, and the black histograms are that for a selected sub-sample. The selection criteria are indicated at the top of each panel. The bottom right panel shows whether or not $|\Delta PA|$ is correlated with the maximum $V_{sys}$ variation amplitude from the tilted-ring decomposition.
logue, with the exception of three objects (NGC 4245, NGC 4314, NGC 7742). For these objects, due to their low inclination, the RC3 does not deliver this value. For these objects, we obtain the stellar PA from the stellar velocity fields, defined as the direction of the maximum stellar velocity gradient. In general, we find that for the stars the photometric and kinematic PA is consistent. A method to quantify the stellar kinematic PA (Kinemetry) of early-type galaxies has been described in Copin et al. (2001) and Krajnović (2004). The method is very similar to the harmonic decomposition that we have introduced in section 3.4. By applying Kinemetry to our stellar velocity fields, one can quantify the stellar kinematics and make a detailed comparison between the stellar kinematic PA with the stellar photometric PA. For the time being, we assume that the RC3 PA values represent the stellar component.

In Fig. 3.13, we present the distribution of the absolute values of the difference between the stellar and the gaseous PA values. We find that the gas kinematics PA for 8/22 early-type spirals are the same as the stellar PA values. This fraction corresponds to $36(\pm5)\%$. In three cases (NGC 4772, NGC 7742 and NGC 5953) we find that the stars and gas are in counter rotation. In NGC 5475, the $\Delta PA = 80^\circ$ is suggestive of the gas being perpendicular to the stars, and in the remaining 10 galaxies, we find considerable misalignment (i.e., $|\Delta PA| \geq 10^\circ$). Taking these three categories, we find that in total 14/22 objects, corresponding to $63(\pm5)\%$, show misaligned gas kinematics. This is consistent with the results from Corsini et al. (2003) and Coccato et al. (2004), who found gas velocity gradient along the optical minor-axis in at least half of a sample of 117 early-type spiral galaxies.

We study the correlation of the misalignment with other observed properties in the host galaxies. In Fig. 3.13, we compare the distribution of the absolute values of the misalignment $|\Delta PA|$ of the entire spiral sample with carefully chosen sub-samples. We find that the strong misalignments are not correlated with the host galaxies being barred as defined by RC3 or having an inner disk component. One possible way to explain this is that the outer gaseous component lies on the plane perpendicular to the minor-axis of the bulge, while the inner gas rotates in the plane perpendicular to the major-axis of the bulge giving rise to an inner polar disk (Corsini et al. 2003). If this is the case the central velocity gradient observed along the disk minor-axis is associated with a central zero-velocity plateau along the disk major-axis. Another possible explanation is that in the presence of a triaxial bulge or a bar, the misalignment is expected (e.g., Zaritsky & Lo 1986; Bertola, Vietri & Zielinger 1991). Importing the latter explanation to the misalignment, we find that $36(\pm5)\%$ of the spirals are consistent with axisymmetric rotation.

We find that discovering the misalignment is equally efficient in low-inclination as in highly inclined spirals. Furthermore, investigating the active galaxies (Seyferts and LINERs) separately, we find that three out of four highly misaligned cases show some activity. We also examine whether stellar and gaseous misalignment correlates
with non-zero difference between the systemic velocity of the gas and stars (see bottom right panel in Fig. 3.13), and find that the two are not linked.

### 3.6.3 Bar Fraction in Spirals

In 54(±5)% of the objects, the kinematic maps exhibit significant non-circular motions. They are probably due to bars or spiral arms. In half of these objects, a bar has been detected in the photometry. In two objects out of the sample (NGC 4235 and NGC 4596), where bars have been detected in the photometry, our kinematic maps have failed to show the signatures of the bars. In the first object, the harmonic decomposition has shown that for the kinematic effects of the spiral arms are stronger than the bar. Consequently, the bar is hidden by the arms. In the latter case (NGC 4596), the bar is much larger than the SAURON field, and superimposed on it the galaxy hosts a large bulge, which may be the reasons that the bar kinematic signatures remains hidden. Furthermore, we have been able to associate significant non-circular motions with elliptical streaming in 4 objects.

Combining these cases with the results from the stellar and gaseous misalignment and their implications on deviations from axisymmetry, we find non-axisymmetric effects in all the sample spirals but NGC 4405. This implies a percentage value of 95(±1)%, which is much higher than previously published values (e.g., Eskridge et al. 2000). This high bar fraction may indicate that either bars are more long-lived than thought, or that bars are destroyed and once again form (e.g., Bournaud & Combes 2002). This result indicates that non-axisymmetric features are probably much more common than is nowadays thought. Since however also spiral arms etc. give rise to non-circular motions, our result should be used with caution.

### 3.6.4 Velocity Dispersion of Stars and Gas

An offset between the central velocity dispersion values for the stars and the gas is another clearly observed feature of our maps. The central value is obtained by taking the average over a central 3″ aperture, and is presented in Fig. 3.14. Once again importing the activity classification from NED, and regarding all Seyferts and LINERs as active spirals, for all the active spiral galaxies, we find that the central velocity dispersion of the gas is greater than that of the stars. This discrepancy suggests that a large fraction of spiral galaxies are the so called σ-drop galaxies (Emsellem et al. 2001), or that they host considerable radial gas motions which causes the central gaseous σ to exceed the central stellar σ. Wozniak & Michel-Dansac (2003) have recently shown that this drop in velocity dispersion seems to be consistent with being due to a young stellar population born from dynamically cold gas accreted in a circumnuclear disk. The presence of such disks can be directly related to the circumnuclear structures required to drive the gas to the very central regions, as nuclear bars or nuclear spirals. Fig. 3.14 illustrates the fact that the active sub-sample (containing
Figure 3.14: Comparing the central velocity dispersion values for the gas and that for the stars. The diagonal line indicates the 1:1-slope, and typical velocity dispersion errors are presented in the top left corner. All gaseous $\sigma$ values have been corrected for an instrumental dispersion of 108 km s$^{-1}$. All the active spirals fall below the 1:1-slope line.

Figure 3.15: Stellar and gaseous misalignment versus central stellar velocity dispersion for active and non-active galaxies. All $\sigma$-values have been averaged over a central 3′′ aperture.

Seyfert and LINERs hosts only), falls below the 1:1-slope line, suggesting that the extra gaseous velocity dispersion is linked with the activity. This is in the line with an unpublished study dealing with the contribution of nuclear activity on central gas velocity dispersion in ellipticals and S0s (Barthel et al. in preparation).

We finally test whether the central velocity dispersion values for active and non-active spirals relate to the stellar and gaseous misalignment (see Fig. 3.15). It has been suggested by P. Barthel (private communication), that the presence of an AGN is connected to the presence of circumnuclear gas and dust which is kinematically offset from the general stellar population. We do not find similar trends for our spiral galaxies. This is, however, not a clear one to one comparison, given that the men-
tioned authors define of AGN activity differently from the one we have used here. More tests need to be done in order to compare the trends.

### 3.6.5 Preliminary Conclusions

In conclusion, we have found that 45(±5)% of our sample exhibit kinematic signatures of an inner disk-like structure; 54(±5)% of our sample spirals display significant non-axisymmetric kinematics; 63(±5)% show the signature of misaligned stellar and gaseous components; 36(±5)% display gas kinematics which is consistent with that of an axisymmetric structure, and there might be indications that 95(±1)% of the spirals are barred. In general, gas rotates faster than the stars. In all the non-Seyferts and non-LINERs the central stellar velocity dispersion of the gas follows that of the stars, whereas in the active galaxies, there is a systematic trend that the central gaseous velocity dispersion is higher than that of the stars.

### 3.6.6 What Next?

To better recognise the kinematic signatures associated with bars, and to give details about other kinematic signatures in the observed velocity fields, in the following chapters of this thesis, we have chosen two prototypes. One should realise that the harmonic decomposition that we have applied to interpret the line-of-sight velocities has to be applied with caution. Many times a galaxy does not contain only one component, and the kinematic effects from all co-existing components are combined. In chapter 4, we study NGC 5448, where the stellar distribution and kinematics are regular and the gas kinematics shows clear departures from circular motion. In chapter 5 we study the well known Seyfert 2 galaxy NGC 1068, and study the stellar component as well as the Hβ and the [O III] gaseous component.

The wealth of information and the current status of the analysis of the kinematic maps show the potential of SAURON for delving into the complex kinematic features associated with the role of bars in the formation history and evolution of spiral galaxies. Similar detailed studies of the entire sample spiral galaxies is needed in order to better understand signatures of non-circular motions in observed velocity fields. However, the current status of the results allows us to draw some conclusions about the overall properties of early-type spiral galaxies.

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Table 3.2: Results from the exponential disk fits as well as the tilted-ring fits in comparison with the photometric PAs, and diagnostics of the SAURON kinematic maps. Plus sign means positive detection, and minus means negative detection of the corresponding component.

| Object     | $V_{\text{sys,df}}$ | $V_{\text{sys,tr}}$ | PA$_{\text{df}}$ | PA$_{\text{tr}}$ | PA$_{\text{stars}}$ | $|\Delta PA|$ | $i$ | OD | ID | FB | KB | KDC | CR | Notes                                      |
|------------|---------------------|---------------------|------------------|------------------|---------------------|--------------|-----|-----|-----|-----|-----|-----|-----|--------------------------------------------|
| NGC1056    | 1565                | 1564                | 165              | 166              | 160                 | 5            | 61  | -   | -   | +   | +   | +   | +   | possible KDC                              |
| NGC2273    | 1887                | 1889                | 32               | 31               | 50                  | 20           | 40  | -   | +   | +   | +   | -   | -   | possible KDC                              |
| NGC2844    | 1483                | 1483                | 20               | 16               | 13                  | 5            | 61  | -   | -   | +   | -   | -   | -   | patchy gas distribution                   |
| NGC3623    | 822                 | 824                 | 200              | 200              | 174                 | 25           | 73  | +   | +   | +   | +   | -   | -   | prominent bar kinematics                  |
| NGC4220    | 943                 | 942                 | 176              | 173              | 141                 | 35           | 69  | -   | -   | -   | +   | -   | -   | possible KDC                              |
| NGC4235    | 2297                | 2291                | 48               | 44               | 48                  | 0            | 77  | +   | +   | -   | +   | -   | -   | possible bar                               |
| NGC4245    | 896                 | 895                 | -3               | -1               | 0$^\dagger$          | 0            | 41  | +   | +   | +   | -   | -   | -   | spiral arm kinematics                      |
| NGC4274    | 932                 | 931                 | 258              | 259              | 102                 | 20           | 68  | +   | +   | +   | +   | -   | -   | prominent bar streaming                    |
| NGC4293    | 942                 | 942                 | 70               | 71               | 72                  | 0            | 63  | +   | -   | +   | +   | -   | -   | odd central gaseous component              |
| NGC4314    | 1004                | 1005                | -54              | -67              | -70$^\dagger$        | 0            | 27  | +   | -   | +   | +   | -   | -   | bar signature                              |
| NGC4369    | 1036                | 1035                | 259              | 258              | 127                 | 50           | 12  | +   | +   | -   | -   | +   | -   | possible KDC                              |
| NGC4383    | 1721                | 1722                | 161              | 157              | 28                  | 40           | 58  | +   | -   | -   | -   | -   | -   | very complex kinematics                    |
| NGC4405    | 1753                | 1753                | 201              | 201              | 20                  | 0            | 50  | +   | -   | -   | -   | +   | -   | possible KDC                              |
| NGC4596    | 1907                | 1909                | 106              | 109              | 135                 | 30           | 42  | +   | +   | -   | -   | -   | -   | no bar detected in the SAURON field        |
| NGC4698    | 1046                | 1052                | 151              | 152              | 170                 | 20           | 52  | +   | +   | +   | +   | -   | -   | KDC                                        |
| NGC4772    | 1044                | 1041                | 34               | 57               | 147                 | 95           | 60  | +   | -   | -   | +   | -   | +   | similar to polar-ring                      |
| NGC5448    | 2036                | 2022                | 117              | 133              | 115                 | 0            | 63  | +   | +   | +   | +   | -   | -   | see chapter 4                              |
| NGC5475    | 1667                | 1669                | 60               | 63               | 166                 | 80           | 76  | +   | -   | -   | -   | +   | -   | similar to polar-ring                      |
| NGC5636    | 1638                | 1642                | 64               | 58               | 40                  | 20           | 44  | +   | -   | -   | +   | -   | -   | regular disk with little gas               |
| NGC5689    | 2213                | 2214                | -96              | -96              | 85                  | 10           | 74  | +   | +   | +   | +   | -   | -   | minor-axis rotation                        |
| NGC5953    | 1984                | 1984                | 262              | 248              | 169                 | 80           | 34  | +   | -   | -   | +   | -   | +   | interacting                                |
| NGC7742    | 1675                | 1673                | 139              | 128              | -40$^\dagger$        | 170          | 10  | +   | -   | -   | -   | +   | +   | ring at 14"                                 |

Notes: (1) Mean $V_{\text{sys}}$ from the exponential disk fit. (2) Mean $V_{\text{sys}}$ from the tilted-ring fit. (3) Mean PA from the exponential disk fit. (4) Mean PA from the tilted-ring fit. (5) PA of the stars from the RC3. $^\dagger$ indicates cases where stellar PA is estimated from our kinematic maps. (6) Absolute value of the difference between the PA of the stars and the gas (in bins of 5°). (7) Inclination from the $R_{25}$. (8) Outer disk rotation. (9) Inner disk structure. (10) Photometrically detected bar. (11) Kinematically detected bar. (12) Kinematically decoupled component. (13) Gas and stars are in counter-rotation. (14) Most prominent observed features. PA and velocity units are degrees and km s$^{-1}$. 
Figure 3.16: R-band Digital Sky Survey images of all our spiral galaxies. The orientation is such that north is up and east is left. The bar located at the bottom-left corner of each image indicates the size of one effective radius (from RC3: de Vaucouleurs et al. 1991). Overlaid on each image is the approximate footprint of the SAURON pointings obtained for that object. Also here are unsharp-masked DSS and SAURON images together with all the kinematic maps as well as the best-fit exponential disk and best-fit harmonic decomposition with corresponding residual maps.
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Preliminary Results

Figure 3.16: continued...
NGC4314

Unsharp Masked DSS

Unsharp Masked SAURON

Stellar Flux

V stars (km/s)

σ stars (km/s)

h3

h4

[OIII] Gas Flux

V [OIII] Gas (km/s)

σ [OIII] Gas (km/s)

Disk Model

Data - Disk Model

Harmonic Fit

Data - Harmonic Fit

Type = SB(rs)a
M_b = -19.55
Incl. = 27 deg
Vsys (DF) = 1003 km/s
Vsys (TR) = 1005 km/s
PA (DF) = -53 deg
PA (TR) = -67 deg

Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Figure 3.16: continued...
Type = SA(r)b
$M_0 = -19.76$
Incl. = 10 deg
Vsys (DF) = 1676 km/s
Vsys (TR) = 1673 km/s
PA (DF) = 139 deg
PA (TR) = 128 deg

Figure 3.16: continued.
Figure 3.17: Results from the harmonic decomposition of the [OIII] gas velocity fields. Sizes of the symbols become smaller for larger rings, to illustrate better the behaviour of the $s_3$ vs. $s_1$ curve.
Figure 3.17: continued...
Figure 3.17: continued...
Figure 3.17: continued...
Figure 3.17: continued...
Figure 3.17: continued.