Chapter 5

Neutral hydrogen and the kinematics of stars and ionised gas in early-type galaxies

*Based on Serra P., Trager, S. C., Oosterloo, T. A., Morganti R. 2008, in preparation*

In this chapter we present the analysis of long-slit stellar and ionised gas kinematics in early-type galaxies (ETGs) in the H I-selected sample described in Chapter 2. Our aim is to understand whether H I content and distribution are of any relevance for ETG stellar kinematics, and whether ETG neutral and ionised gas-phases are related to each other. As in previous studies, we find ETGs with different amounts of rotational support, stellar kinematically-decoupled cores, and ionised gas usually kinematically decoupled from the stars. Considering the original aspect of this investigation, no strong relation emerges between stellar kinematics and H I distribution. The H I content or morphology does not seem to be relevant for the amount of rotational support to galaxy shape. Furthermore, galaxies with or without kinematical signatures of a disc component are found at any H I mass and morphology.

Regarding the connection between ionised and neutral gas, H I and ionised gas seem to have consistent kinematics in H I-rich systems where the neutral hydrogen extends down to the stellar body, and H I-poor galaxies have little ionised gas. Therefore, it is possible that H I and ionised gas generally belong to a same structure. Finally, building upon the results of Chapter 4, we investigate whether stellar populations are related in any way to the kinematical properties of ETGs. Again, we find no clear relation.

In what follows we analyse new 21-cm observations of three galaxies in the sample in Sec.5.1. We use these data and those presented in Chapters 2 and 3 in order to analyse the connection between ETG H I phase and their stellar and ionised gas kinematics in the rest of this chapter. We derive and discuss stellar and ionised-gas kinematics of all galaxies in the sample in Sec.5.2. We analyse the relation between stellar kinematics, ionised-gas kinematics and H I properties in Sec.5.3 and investigate whether stellar kinematics and populations are related to each other in Sec.5.4. We conclude with a
Table 5.1: ATCA observations

<table>
<thead>
<tr>
<th></th>
<th>ESO092-21</th>
<th>ESO 140-31</th>
<th>ESO 381-47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre RA (J2000)</td>
<td>10:21:05.50</td>
<td>18:37:53.60</td>
<td>13:01:05.40</td>
</tr>
<tr>
<td>Centre Dec (J2000)</td>
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<td>–57:36:40.0</td>
<td>–35:36:60.0</td>
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<tr>
<td>Frequency (MHz)</td>
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<td>1407</td>
<td>1398</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
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<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Number of channels</td>
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<td>512</td>
<td>512</td>
</tr>
<tr>
<td>Velocity resolution (km/s)</td>
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<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Total integration (h)</td>
<td>3×12</td>
<td>3×6</td>
<td>3×12</td>
</tr>
<tr>
<td>Integration in 705A (h)</td>
<td>2×12</td>
<td>2×6</td>
<td>2×12</td>
</tr>
<tr>
<td>Integration in EW367 (h)</td>
<td>12</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>robust</td>
<td>0.5</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>Synthesised beam FWHM</td>
<td>66′×57″</td>
<td>78′×67″</td>
<td>92′×65″</td>
</tr>
<tr>
<td>PA (deg)</td>
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<td>-5</td>
<td>8</td>
</tr>
<tr>
<td>RMS noise (mJy/beam)</td>
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<td>1.3</td>
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</tr>
<tr>
<td>Maximum signal (mJy/beam)</td>
<td>60.7</td>
<td>29.3</td>
<td>20.7</td>
</tr>
</tbody>
</table>

(1) After Hanning smoothing.

summary of our findings and an appendix with the description of the kinematics of stars and ionised gas in individual objects.

5.1 Three H i-rich southern galaxies

In Chapter 2 we present the sample of ETGs selected to investigate the relation between H i and stellar properties in this class of objects. There we discuss how the H i is distributed around individual gas-rich galaxies on the basis of available interferometry. As a part of this thesis project, we have re-observed with the Australia Telescope Compact Array (ATCA) four of the 22 H i-detected galaxies described in Chapter 2. These four galaxies had been previously studied with short ATCA-integrations by [Oosterloo et al. (2007b); hereafter OMSHS07]. New observations of one of them, IC 4200, are discussed in Chapter 3. New ATCA interferometry of the remaining three objects is presented here. The three galaxies are ESO 092-21, ESO 140-31 and ESO 381-47.

5.1.1 ATCA observations and data reduction

Table 5.1 summarises the parameters of our new ATCA observations and the resulting properties of the data-cubes. ESO 092-21 and ESO 381-47 were observed for a total of 3×12 hours, of which 2×12 hours with the configuration 705A and 12 hours with the more compact EW367. The latter is chosen in order to increase the sensitivity to extended, low-column-density emission. ESO 140-31 was observed for only half of this time in each configuration. These are the same configurations used for IC 4200 (see Table 3.2).

Observations were carried out with a 16-MHz bandwidth and 512 channels giving a velocity resolution of 13 km/s after Hanning smoothing. Bandpass, flux-density scale
5.1: Three H i-rich southern galaxies

Figure 5.1: Left panel: H i surface-brightness contours on top of a DSS image for ESO 092-21. Contour levels go from 0.68 to $5.81 \times 10^{20}$ cm$^{-2}$ with steps of $1.03 \times 10^{20}$ cm$^{-2}$. The maximum measured column density is $6.84 \times 10^{20}$ cm$^{-2}$. The beam is shown in the bottom left. Its size is $66 \times 57$ arcsec$^2$ FWHM with PA=72 deg. The total H i mass is $5.6 \times 10^9$ $M_\odot$ assuming the distance in Table 2.1. Right panel: position-velocity diagram of ESO 092-21 H i emission along PA=51 deg, which corresponds to the H i kinematical major axis as well as the optical morphological one. North-east is to the left.

and gain-changes were determined by observing a primary and a secondary calibrator. Data reduction was performed in the standard way using the MIRIAD package (Sault et al. 1995). Continuum emission was modelled by linear fitting through the line-free channels in the UV plane, and then subtracted. The H i cubes presented here are obtained inverting the UV data with $robust=0.5$ for ESO 092-21 and ESO 381-47. We use $robust=2$ for ESO 140-31 because the shorter integration time results in a worse sensitivity (for details on the $robust$ parameter see Briggs 1995). The noise level in the final data-cubes is reported in Table 5.1.

Total-intensity H i images are obtained by adopting different masking methods in order not to miss any emission. For ESO 092-21, we mask out all pixels with flux density below 4 $\sigma$. For ESO 140-31, we select pixels above 5 $\sigma$ in either the original cube or the 100-arcsec-smoothed one. For ESO 381-47, we require the flux density to be above 4 $\sigma$ in the original cube or in the 180-arcsec-smoothed one. Below we show the result of these observations.

5.1.2 ESO 092-21

We detect $5.6 \times 10^9$ $M_\odot$ of H i distributed over a regularly-rotating disc with radius of $\sim$25 kpc. Fig 5.1 (left panel) shows the H i surface-brightness contours on top of an optical image. The new data represent a substantial improvement over the data of OMSHS07, which were affected by radio-frequency interference. Such interference might be the reason why our measured H i-flux is $\sim$30% larger than in OMSHS07. As usual in ETGs, the H i is at column density of at most a few times $10^{20}$ cm$^{-2}$, so that large-scale star formation is not expected. However, Helmboldt et al. (2005) detected hundreds of H ii regions brighter than $10^{38}$ erg/s spread over the H i disc surrounding ESO 092-21.
Figure 5.2: Constant-DEC slices of ESO 092-21 H\,I data-cube (grey scale) with a declining-rotation-curve model overlaid (contours; see text). DEC increases from left to right, top to bottom with steps of 1 arcmin. The top-left slice is at DEC=−66° 27′ 0″.
This indicates that, locally, star formation may be occurring.

The H i column density peaks along the disc major axis at two positions slightly off-centre. It is therefore possible that no neutral gas resides within the stellar body. However, the beam size of our radio observations is a few times the size of the stellar body itself, so that no firm conclusion can be drawn.

In Fig. 5.1 (right panel) we plot the velocity of the H i emission as a function of radius along the kinematical major axis of the disc. The latter (PA=51 deg) corresponds to optical as well as H i morphological major axis. The gas rotation is very regular. The line-of-sight (l.o.s.) rotational velocity falls slightly at large radius. This could be due to either a real decline of the rotation curve because of a steepening of the total mass profile (within Newtonian dynamics); or to a warp that causes the outer-disc to be seen at lower inclination on the line of sight, with a resulting decrease in the l.o.s. rotational velocity. This later interpretation might be supported by the fact that the observed rotation declines faster on the south-west side. Asymmetries are indeed a common characteristic of warped discs (e.g., García-Ruiz et al. 2002).

We have investigated these two possibilities by building models of the H i disc. For this purpose we have used a Python code written by PS which constructs tilted-ring models smoothed to the instrumental resolution from a simple set of input parameters (the code is freely available at www.astro.rug.nl/~pserra/). Fig. 5.2 shows constant-DEC slices of the observed cube (grey scale) with the best (by eye) model superimposed (contours). The model consists of a disc with radius 170 arcsec (25.3 kpc), constant gas density, inclination of 47 deg, position angle of 50 deg, and rotational velocity of 200 km/s out to 60 arcsec from the centre and falling linearly to 180 km/s at 170 arcsec. We assume a gas velocity-dispersion of 10 km/s. A nearly identical model can be built by keeping the rotational velocity fixed at 200 km/s and linearly decreasing the disc inclination from 47 to 41 deg between 60 and 170 arcsec from the centre. The resolution of our data is not sufficient to distinguish between the two possibilities. The model shown in Fig. 5.2 is not a fit to the data but, within the degeneracy between warp and declining-rotation, only minor variations are allowed.

Given the regular appearance of the disc, we can estimate the dynamical mass of ESO 092-21 by assuming circular gas orbits in equilibrium inside a spherical mass distribution. Adopting Newtonian dynamics and the H i warped-disc model with flat rotation, \( M_{\text{dyn}} \approx 2.4 \times 10^{11} \, M_{\odot} \) at 25.3 kpc. As a comparison, given the metallicity measured in Chapter 4 and assuming \( B - V \approx 0.9 \), Bruzual & Charlot (2003) models give a stellar mass-to-light ratio of about 6.5 \( M_{\odot}/L_{\odot} \) in B band. ESO 092-21 has \( L_B = 8.9 \times 10^9 \, L_{\odot} \), which corresponds to a total stellar mass of \( 5.8 \times 10^{10} \, M_{\odot} \). This is a factor of 4 smaller than \( M_{\text{dyn}} \).

### 5.1.3 ESO 140-31

We detect \( 1.56 \times 10^9 \, M_{\odot} \) of H i associated with ESO 140-31. This is about half of the H i mass reported by OMSHS07 (at the same galaxy distance). The reason of this difference is not clear and may be our use of longer baselines and the different masking schemes adopted when deriving the total H i image. Besides this discrepancy, the new data confirm that the galaxy resides in a gas-rich environment (see Fig. 5.3). Three more galaxies are detected within 200 kpc from ESO 140-31. Two of them have \( M(\text{H} \, \text{i}) \) comparable to that of our target. They are the late-type spiral IC 4736 to the
Figure 5.3: H I surface-brightness contours on top of a DSS image for ESO 140-31. ESO 140-31 is the galaxy in the centre of the field. Contours go from $0.22$ to $5.27 \times 10^{20}$ cm$^{-2}$ with steps of $0.56 \times 10^{20}$ cm$^{-2}$. The maximum measured column density is $5.61 \times 10^{20}$ cm$^{-2}$. The beam is showed in the bottom left. Its size is $78 \times 67$ arcsec$^2$ FWHM with $PA=-5$ deg. In the figure, we report next to each detected object the H I mass in $10^9 M_\odot$.

Figure 5.4: Position-velocity diagram taken along an axis going through the centres of ESO 140-31, IC 4736 and PGC 062147 ($PA=160$ deg). South is to the right. The emission associated with ESO 140-31 lies in the middle of the plot (offset$\sim$3 arcmin).
Three H i-rich southern galaxies

5.1: Three H i-rich southern galaxies

south ($B=14.6$; for comparison, ESO 140-31 has $B=13.6$), and the low-surface-brightness irregular PGC 062147 to the north ($B=15.9$). The fourth H i-detection, lying $\sim 60$ kpc to the west of ESO 140-31, has as a small, unidentified optical counterpart in DSS. No H i is detected between this galaxy and ESO 140-31, so that there is no evidence of on-going or recent interaction.

With respect to the observations presented in OMSHS07, the new data allow a more detailed investigation of the neutral hydrogen properties. The H i around ESO 140-31 is elongated in a direction orthogonal to the major axis of the stellar body (i.e., $PA=170$ deg) and extends out to 35 kpc from it. The structure is seen edge-on or nearly so. The H i is not perfectly symmetric around the centre of the galaxy, with the southern edge being slightly broader and brighter than the northern one. The H i distribution becomes narrower when moving towards smaller radii, suggesting the presence of a central hole in the gas density. However, the gas distribution is barely (or not) resolved along the east-west direction. More complicated configurations not requiring a central H i hole are therefore possible (e.g., a warp with $PA$ raising above and then dropping below $PA=170$ deg, or vice-versa, as the radius increases). Within the limitations of these data, the gas appears to be regularly rotating at $\sim 150$ km/s with kinematical major axis at $PA\sim 170$ deg. Fig.5.4 shows an H i position-velocity diagram along an axis going through the centres of ESO 140-31, IC 4736 and PGC 062147 ($PA=160$ deg). The three galaxies have very similar velocities. The third, unidentified companion galaxy (west of ESO 140-31 and not shown in Fig.5.4) is detected at slightly lower velocity (it spans the velocity range 2815-2910 km/s). The appearance of the H i around ESO 140-31 in Fig.5.4 confirms a decline of the gas surface-density towards the galaxy centre.

Since the observed l.o.s. rotational velocity varies as $\sin(i)$, where $i$ is the disc/ring inclination, near to edge-on it does not deviate much from the actual rotation. Assuming therefore that the gas rotates in equilibrium at the observed 150 km/s at 35 kpc from the centre of ESO 140-31, we derive a dynamical mass $M_{\text{dyn}}=1.8\times10^{11} M_\odot$. As done for ESO 092-21, we can compare this value to an estimate of the stellar mass. Given the metallicity measured in Chapter 4 and assuming $B-V \sim 0.9$, Bruzual & Charlot (2003) models give a stellar mass-to-light ratio of about 7.7 $M_\odot/L_\odot$ in $B$ band. ESO 140-31 has $L_B=1.6\times10^{10} L_\odot$, which corresponds to a total stellar mass of $1.3\times10^{11} M_\odot$. This is just below $M_{\text{dyn}}$. A reasonably redder colour would bring the stellar mass estimate even closer to $M_{\text{dyn}}$. However, better H i observations would be necessary to clarify whether the H i is regularly rotating and what the inclination of the ring/diks is. For example, emission along the minor axis is typically fainter (per velocity channel) than along the major axis. Given that the detected emission is close to the noise, it is possible that we are missing some emission along the minor axis so that the disc/ring looks more edge-on than it actually is.

5.1.4 ESO 381-47

Fig.5.5 shows the H i surface-brightness contours derived from our observation of ESO 381-47. Our estimate of the total H i flux associated with the galaxy is in good agreement with OMSHS07 result. As for ESO 140-31, the observations reveal a very H i-rich environment. The total H i mass of the group is about $10^{10} M_\odot$, most of which is associated with ESO 381-47 (8.16$\times10^9 M_\odot$). The detected companions (all disc galaxies) are: at the southern edge of the field, the Sc ESO 381-46 ($B=15.5$; for comparison, ESO
**Figure 5.5:** $\text{H} \text{\textsc{i}}$ surface-brightness contours on top of a DSS image for ESO 381-47. Contours go from $0.21$ to $2.03 \times 10^{20}$ cm$^{-2}$ with steps of $0.23 \times 10^{20}$ cm$^{-2}$. The maximum measured column density is $2.28 \times 10^{20}$ cm$^{-2}$. The beam is showed in the bottom left. Its size is $92 \times 65$ arcsec$^2$ FWHM with $PA=8$ deg. In the figure, we report next to each detected object the $\text{H} \text{\textsc{i}}$ mass in $10^9 M_\odot$. ESO 381-47 is the galaxy on the north with the most extended $\text{H} \text{\textsc{i}}$ emission.

**Figure 5.6:** Position-velocity diagram along $PA=10$ and centred on ESO381-47. South is to the right.
Figure 5.7: H\textsc{i} total surface-brightness image (grey scale) with velocity-field contours over-plotted in white. The iso-velocity contours correspond to velocities from 4710 to 4785 with step of 15 km/s. Lower velocities are on the south side. The synthesised beam is shown in the bottom-left corner and is the same as in Fig.5.5.

381-47 has $B=14.0$; to the east, the edge-on 2MFGC 10338 ($B=16.2$); to the southwest, two nearly edge-on galaxies, ESO 381-43 (farther away from ESO 381-47 and with $B=16.7$) and an unidentified object.

ESO 381-47 hosts a massive, extended, low-inclination ring with a resolved hole in the centre (see grey scale H\textsc{i} image in Fig.5.7). The kinematics of the H\textsc{i} is quite regular but far from the ideal case of a flat, rotating ring. Fig.5.6 shows a position-velocity diagram along $PA=10$ deg. Along with bright emission corresponding to the regularly-rotating gas, H\textsc{i} is observed at a velocity close to systemic at large radius, in particular on the north side. The location of this gas on the position-velocity diagram is not consistent with coplanar circular orbits. Given the low inclination, a strong warp could cause the l.o.s. velocity of the H\textsc{i} to go back to systemic at large radius. A strong warp is indeed observed. For example, it can be seen in the velocity field in Fig.5.7 (white iso-velocity contours on top of the H\textsc{i} surface-brightness image). The velocity field is obtained after masking out the gas at anomalous velocity visible in Fig.5.6. The twist of the kinematical major axis towards larger $PA$ as the radius increases can be modelled with a warped ring. The outer, systemic-velocity emission might fall within the same model if the ring keeps warping out to the largest radius. We have additional Very Large
Array (VLA) observations of this galaxy which support such a conclusion. The analysis of these data is work in progress with Jennifer Donovan, Jacqueline van Gorkom and John Hibbard. As part of this collaboration, ESO 381-47 was observed with GALEX in the ultraviolet. These observations revealed a UV ring coincident with the peak of the H\textsc{i} emission. ESO 381-47 is therefore, along with ESO 092-21, another case of a galaxy whose H\textsc{i} reservoir may trigger some morphological transformation.

5.2 Optical spectroscopy: stellar and ionised-gas kinematics

5.2.1 Data analysis

Long-slit optical spectroscopy of all 39 galaxies in the sample is presented in Chapter 4. We refer to that chapter for details on observations and data reduction. We recall here that spectra are taken along two perpendicular slit positions aligned (with a few exceptions) to optical major and minor axis respectively. In Chapter 4 we use these data to analyse galaxy stellar populations and ionised-gas content over two apertures. Here we use the same data to derive stellar and ionised-gas kinematics along the two axes.

To recover stellar and ionised-gas line-of-sight velocity distribution (LOSVD) as a function of radius, we extract from each galaxy long-slit spectrum a number of one-dimensional spectra within radial bins of S/N $\sim$30/Å at $\sim$5000 Å. We then run GANDALF (Sarzi et al. 2006) on each bin. This allows us to disentangle stellar and ionised-gas contribution to the spectrum and obtain the LOSVD of both. Namely, the stellar LOSVD is approximated by a Gauss-Hermit expansion up to the fourth-order term, giving $v_{\text{star}}$, $\sigma_{\text{star}}$, $h_3$ and $h_4$. These represent, respectively the recessional velocity of the stellar absorption-line spectrum, the stellar velocity dispersion causing the line broadening, the skewness of the lines, so that positive values of $h_3$ correspond to an extended tail towards velocities higher than $v_{\text{star}}$, and the kurtosis of the lines, with positive $h_4$ values associated with lines narrower than a Gaussian. Ionised-gas emission lines are fitted with Gaussian curves whose centre and width give $v_{\text{gas}}$ and $\sigma_{\text{gas}}$ respectively.

In Chapter 4 we use GANDALF to remove the ionised-gas contribution before measuring stellar line-strength indices for the stellar-population study. Here we use the same GANDALF set-up as in Chapter 4. The only difference is that for all galaxies, after a first fit where all emission lines are masked out, we fit again the stellar spectrum together with the [O \textsc{iii}]$_{\lambda5007}$ line only. We then repeat the fit including all emission lines and forcing them to have the same kinematics as [O \textsc{iii}]$_{\lambda5007}$. Finally, as in Chapter 4, we fit again, letting all lines brighter than $A/N=5$ be kinematically independent ($A$ is the Gaussian-fit amplitude and $N$ is the median noise in a narrow wavelength range centred on the line). We consider a line detected if $A/N \geq 3$. The final result is a table of stellar and emission-line LOSVD as a function of radius for each galaxy along each of the two slit positions.

5.2.2 Error analysis

We estimate the uncertainty on the stellar LOSVD parameters by means of Monte Carlo simulations. For this purpose, we choose randomly, among all galaxies and radial bins, one of the bins of NGC 3108. We assume that the flux at each pixel follows a Gaussian
5.2: Optical spectroscopy: stellar and ionised-gas kinematics

distribution with mean value equal to the measured flux and rms deviation equal to the estimated noise. We then run GANDALF on each of the 200 realisations of the spectrum. The rms deviation of the derived $v_{\text{star}}$, $\sigma_{\text{star}}$, $h_3$ and $h_4$ from their mean values is 8 km/s, 11 km/s, 0.02 and 0.02 respectively. The $\chi^2$ of the fit is 1.21±0.02. Since all radial bins are built so to have the same $S/N$, we expect these error estimates to be appropriate for all radial bins of all galaxies. In fact, the error on the LOSVD parameters is likely to vary depending on the stellar velocity dispersion of the galaxy. The radial bin used for this experiment has $\sigma_{\text{star}}=219$ km/s, well above the instrumental dispersion. We have re-run the same experiment with two spectral bins chosen among the ones of NGC 1426 and NGC 4278 respectively. The result is an rms deviation of $v_{\text{star}}$, $\sigma_{\text{star}}$, $h_3$ and $h_4$ from their mean values of 2 km/s, 4 km/s, 0.01 and 0.02 respectively for the NGC 1426 bin ($\sigma_{\text{star}}=129$ km/s; $\chi^2=1.84±0.03$); and of 4 km/s, 4 km/s, 0.01 and 0.01 respectively for the NGC 4278 bin ($\sigma_{\text{star}}=301$ km/s; $\chi^2=2.06±0.03$). The latter is the central bin of NGC 4278. Its $S/N$ ratio is actually higher than for other bins, so that the uncertainties on the stellar-LOSVD parameters are quite low. This is the case for the central spectral bins of most galaxies.

The error on $v_{\text{gas}}$ and $\sigma_{\text{gas}}$ is more difficult to estimate because it depends on the brightness of the line used for the measurement. For a given emission line, this varies widely from galaxy to galaxy so that a good error estimate valid for all spectral bins of all objects (and all emission lines) cannot be obtained from a generic spectrum. With respect to the spectral bin extracted from the long-slit spectrum of NGC 3108 and used to estimate the uncertainty on the stellar LOSVD, [O III]$_{\lambda 5007}$ is detected with $A/N=9.4±0.6$. Its $v_{\text{gas}}$ and $\sigma_{\text{gas}}$ vary around their mean values with rms deviation of 13 and 22 km/s respectively. The mean velocity dispersion of the gas is $\sim 129$ km/s. In this chapter we only discuss the ionised-gas kinematics derived from the [O III]$_{\lambda 5007}$ line. However, one should keep in mind that different emission lines, which may have been fitted with kinematics independent from that of the [O III]$_{\lambda 5007}$ line, may have slightly different uncertainties on $v_{\text{gas}}$ and $\sigma_{\text{gas}}$. In general, the errors on $v_{\text{gas}}$ and $\sigma_{\text{gas}}$ are likely to be at least twice as large as those on $v_{\text{star}}$ and $\sigma_{\text{star}}$.

5.2.3 Results

Fig. 5.8 shows, for each object in the sample and along each long-slit $PA$, $v_{\text{star}}$, $\sigma_{\text{star}}$, $h_3$, $v_{\text{gas}}$ and $\sigma_{\text{gas}}$ as a function of the distance from the centre of the galaxy. For each galaxy, eight panels are given. The panels are arranged in two columns of four panels each. Each column corresponds to the $PA$ indicated on the top. The first column (left) gives the kinematics along the axis closer to the morphological major axis. The $PA$ of the latter is taken, when available, from de Vaucouleurs et al. (1991, RC3). Major-axis position-angle values $PA_{\text{RC3}}$ are listed in Table 5.2. In the same table, we give galaxies’ ellipticity $\epsilon_{\text{RC3}}$ taken from the same catalogue. We note here that the major axis of NGC 0636 is at $PA_{\text{RC3}}=6$ deg but, in fact, Rembold et al. (2002) find $PA\approx 90$ deg in the inner regions in the infrared (a strong $PA$ twist is reported for this galaxy also by Franz et al. 1989b and Michard & Marchal 1994). The first two panels (from top to bottom) in Fig. 5.8 show respectively velocity and velocity dispersion of stars (asterisks) and ionised gas ([O III]$_{\lambda 5007}$ line, open circles). Velocities are meant with respect to an arbitrary zero-point indicated for each galaxy in the top-left corner of the top-left panel. The shift in velocity was chosen so to have $v_{\text{star}}=0$ at the central bin along one of the two axes.
The ionised-gas kinematics is plotted only when the [O iii]λ5007 line is detected with $A/N \geq 3$ (see above). Smaller open circles are used if $A/N \leq 5$. The bottom two panels show the stellar $h_3$ and $h_4$ (asterisks). For some galaxies, dashed lines and small crosses show literature data used as a comparison to our results (see below). The slit orientation is given at the bottom of the bottom panel for each slit PA. Typical error bars on $v_{\text{star}}$ (8 km/s), $\sigma_{\text{star}}$ (11 km/s), $h_3$ (0.02) and $h_4$ (0.02) are shown on the top-right corner of the respective right-side panels. For each galaxy, the 1 kpc scale is shown at the top of the top-right panel. This is obtained assuming the distance in Table 2.1 and $H_0=70$ km/s Mpc$^{-1}$. For a given galaxy, the scale of the radial, $v$, $\sigma$, $h_3$ and $h_4$ axes does not vary from panel to panel. We refer to Appendix 5.A for a discussion of individual cases. Here we discuss some general features that emerge from these observations.

Fig. 5.8 gives an idea of the kinematical variety of the observed galaxies. Concerning the stellar kinematics, we go from galaxies with a significant amount of rotation observed along the major axis (e.g., IC 4200, IC 4889, NGC 1490, NGC 3610) to minor-axis rotators (NGC 0596, NGC 2300) and galaxies with little or no rotation along both axes (e.g., NGC 2434, NGC 7585) even when significantly flattened (e.g., ESO 092-21, NGC 5903). The $\sigma_{\text{star}}$ profiles vary also widely, going from raising ones (e.g., NGC 1490, NGC 2434, NGC 7332, NGC 7619) to central plateau (e.g., ESO 140-31, NGC 1947, NGC 3108, NGC 3193) or dips (e.g., NGC 0596, NGC 2768, NGC 4125). Finally, $h_3$ is anti-correlated with $v_{\text{star}}$ in most cases where stellar rotation is detected. Exceptions are, for example, IC 4200, NGC 3640, NGC 4125.

The detection of $\sigma$ plateau or dips may be interpreted as a signature of a kinematically-cold stellar structure on top of the underlying pressure-supported bulge (e.g., Wozniak et al. 2003; Falcón-Barroso et al. 2006; Ganda et al. 2006). However, theoretical prediction of such $\sigma_{\text{star}}$ minima in ETGs was made by Binney (1980) for $r^{1/4}$-profile galaxies, and generalised to isotropic and anisotropic $r^{1/n}$ systems by Ciotti (1991) and Ciotti & Lanzoni (1997). Therefore, stellar discs are not necessarily required to explain the $\sigma_{\text{star}}$ dips. Considering also that the interplay between velocity-dispersion anisotropy and l.o.s. projection can change the observed $\sigma_{\text{star}}$ profile, an interpretation of the central dips is not straightforward.

On the other hand, the anti-correlation between $v_{\text{star}}$ and $h_3$ found in many galaxies is a signature of the existence of a rotating stellar system on top of a non-rotating one (e.g., Bender 1990). The reason is that such rotating sub-component shifts the peak of the stellar LOSVD towards the rotational velocity, generating an extended tail away from it and therefore towards systemic. At the low $v/\sigma$ typical of ETGs, such anti-correlation cannot be explained by l.o.s. integration along a one-component rotating system, even when close to edge-on (Bender 1990).

In some galaxies we find $v_{\text{star}}$ central dips (NGC 1426, NGC 2768, NGC 3610, NGC 3998, NGC 5173, NGC 5322). Assuming that the stellar body is in equilibrium within the potential, such features should not be found along any axis passing through the galaxy centre. However, all $v_{\text{star}}$ dips are detected along slit positions perpendicular to the axis where we measure rotation, and mostly when the latter raises steeply. Therefore, they could be due to poor slit centring. Indeed, the dips are always consistent with the velocity gradient measured along the perpendicular direction. Poor centring can also cause a peak in $v_{\text{star}}$. Indeed, we find $v_{\text{star}}$ peaks in NGC 4406 and NGC 5018. In the latter, the peak is too large with respect to the rotation along the perpendicular PA, but the galaxy is very disturbed so that unsettled motion might be the cause of the anomaly.
Figure 5.8: Stellar and ionised-gas kinematics of ETGs in the sample. See Sec. 5.2.3 for an explanation of the figure.
Figure 5.8: Continued
Figure 5.8: Continued
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Figure 5.8: Continued
Figure 5.8: Continued
Figure 5.8: Continued
Figure 5.8: Continued
Figure 5.8: Continued
A general feature of Fig.5.8 is that the ionised gas, when detected, does not share the same kinematics of the stars. In many cases the gas is rotating along an axis where stars do not rotate (e.g., IC 4200, IC 4889, NGC 1947, NGC 3108). More in general, even when the projected angular momenta of gas and stars may share the same orientation, the gradients of \( v_{\text{star}} \) and \( v_{\text{gas}} \) are very different (e.g., ESO 140-31, NGC 4125, NGC 4278). In a few cases the ionised gas exhibits chaotic kinematics. This occurs normally in galaxies where the ionised-gas emission is faint (e.g., NGC 2434, NGC 2549, NGC 7332). As far as it is possible to tell from our long-slit data, the only galaxy in which stars and ionised-gas may share the same kinematics is NGC 4026.

The kinematical decoupling of stars and ionised gas was already known to be a characteristic of ETGs (e.g., Bertola et al. 1995; Caon et al. 2000). The recent SAURON survey has provided stellar and ionised-gas velocity fields that allow a full, 2D view of this decoupling over a large fraction of the stellar body (Sarzi et al. 2006). Although more limited, our long-slit spectroscopy confirms their findings.

Many objects stand out as particularly interesting. For example, IC 4889 shows an inner stellar KDC along \( PA=0 \) deg which is counter-rotating with respect to the outer region. The kinematics of the KDC follows that of the ionised gas, which then extends further to outer radii. Along the same \( PA \), a \( \sigma_{\text{star}}\)-dip corresponds to the KDC, while \( h_3 \) is anti-correlated with \( v_{\text{star}} \). Along the perpendicular axis, no stellar rotation is observed while the gas is clearly rotating. Many of these elements point towards there being an inner disc misaligned with respect to the larger-scale stellar rotation. Its stellar component is prominent in the centre, allowing the detection of the KDC and of the \( \sigma_{\text{star}} \) dip. However, the disc itself extends at least 3 times further, as revealed by the extension of the ionised gas kinematics. The presence of a disc is confirmed by the \( v_{\text{star}}-h_3 \) anti-correlation. The kinematics of the ionised gas may imply that its kinematical major axis is at a \( PA \) intermediate between the two slit positions, i.e., \(~45\) deg, with lower l.o.s. velocity towards north-east. Pending the uncertainties caused by the poor resolution of the 21-cm interferometry, this result is consistent with the H\( \text{I} \) kinematics (see Fig.2.11). Our results for this galaxy are consistent with previous work (Bertola et al. 1992a; Carollo et al. 1993; Corsini et al. 2000). KDCs are found at different levels also in NGC 1439, NGC 2434, NGC 4406, NGC 4472, NGC 5322 (some of these were already known from previous studies; e.g., NGC 4406 in Franx et al. 1989a).

While it is certainly interesting to examine individual galaxies in detail, our purpose here is rather to investigate whether the presence and distribution of H\( \text{I} \) is in general related to stellar and ionised-gas kinematics. After comparing our results to previous works, we investigate these connections in Sec.5.3. A discussion of the kinematical properties of individual galaxies can be found in Appendix 5.A.

### 5.2.4 Comparison to previous results

In this section we compare our results to those obtained by previous authors for some of the galaxies in the sample. Namely, we compare our results to those of Emsellem et al. (2004) and Bender et al. (1994). The former present integral-field stellar kinematics of a sample of 48 nearby ETGs obtained within the SAURON project. The latter analyse the stellar kinematics derived from long-slit spectroscopic observations of 44 local ETGs.

Five galaxies of our sample, NGC 2549, NGC 2768, NGC 4278, NGC 7332 and NGC 7457 were studied by Emsellem et al. (2004). For each of them, we used the...
published SAURON kinematics maps to extract $v_{\text{star}}$, $\sigma_{\text{star}}$, $h_3$ and $h_4$ curves along two axes corresponding to our long-slit position-angles and centred on the galaxy centre. We show these curves with dashed lines on top of our measurements in Fig.5.8 (no error maps are available via the SAURON website yet). The agreement is very good for NGC 2549, NGC 4278, NGC 7332 and NGC 7457. In NGC 2768, our $h_4$ measurements seem systematically larger than the SAURON ones by $\sim 0.05$, and $v_{\text{star}}$ exhibits a $\sim 20$-km/s offset and a central dip along $PA=5$ deg. Placing a slit $\sim 1$ arcsec off-centre along $PA=5$ deg, the SAURON data show a similar $v_{\text{star}}$ dip.

Nine galaxies in our sample were studied by Bender et al. (1994; BSG94). These are NGC 2300, NGC 3193, NGC 3610, NGC 3640, NGC 4125, NGC 4278 (already compared to the SAURON results), NGC 4406, NGC 4472 and NGC 5322. In Fig.5.8 we show the comparison of our results to BSG94 $v_{\text{star}}$ and $\sigma_{\text{star}}$ measurements retrieved from the HyperLeda website. BSG94 values are shown as small crosses; dashed lines indicate the $\pm 1\sigma$ interval. BSG94 observations consist, as ours, of long-slit spectroscopy along a number of axes. Since, for a given galaxy, the slit position-angles adopted by BSG94 are not exactly the same as ours, and offsets are possible, we do not expect a perfect agreement. In detail, NGC 2300 was observed by BSG94 along $PA=80$ and 170 deg; NGC 3193 along $PA=3$ and 92 deg; NGC 3610 along $PA=45$ and 135 deg; NGC 3640 along $PA=0$ and 90 deg; NGC 4125 along $PA=82$ deg; NGC 4406 along $PA=30$ and 120 deg; NGC 4472 along $PA=70$ and 160 deg; NGC 5322 along $PA=8$ and 98 deg. Fig.5.8 shows that, despite these differences, our results are consistent with those of BSG94. Comments on the detailed kinematics of individual galaxies and on the comparison to previous results (also other than those of Emsellem et al. 2004 and BSG94) can be found in Appendix 5.A.

5.3 Comparison to H I properties

5.3.1 Stellar kinematics, H I and the $v/\sigma$ vs. $\epsilon$ diagram

In Fig.5.9 we plot all 39 galaxies on the $(\epsilon, v/\sigma)$ plane. $\epsilon$ is the observed ellipticity and $v/\sigma$ is the ratio of the maximum l.o.s. stellar rotation $v_{\text{max}}$ to the average velocity dispersion $\bar{\sigma}$ within the stellar body. Values of $v_{\text{max}}$, $\bar{\sigma}$, $v/\sigma$ and $\epsilon$ are listed in Table 5.2.

For each galaxy, we estimate $v_{\text{max}}$ along a given $PA$ as half the maximum velocity-difference between two points symmetric with respect to the galaxy centre. In doing so, we do not consider the velocity measurements taken at the location of KDCs (e.g., the centre of NGC 4406 along $PA=120$ deg). We take the largest of the two values obtained along the two perpendicular slit positions as the final $v_{\text{max}}$. As error, we take $\delta v/\sqrt{2}$ where $\delta v=8$ km/s (Sec.5.2.2). We assume $v_{\text{max}}=0$ in NGC 7626. For this galaxy, the criterion used for all the other objects would give $v_{\text{max}}=16$ km/s which, looking at Fig.5.8, is meaningless.

We adopt $\sigma_{R_e/16}$ as an estimate of $\bar{\sigma}$. $\sigma_{R_e/16}$ is the stellar velocity dispersion within the inner $R_e/16$ measured in Chapter 4 from our long-slit spectra (see Table 2.1). As explained there, $R_e$ is an estimate of the bulge effective radius derived from the same data. Values of $\sigma_{R_e/16}$ were used in Chapter 2 to divide the sample in the low-, intermediate- and high-$\sigma$ sub-samples. We compared these values to those measured within $R_e/2$. This was done to make sure that adopting the former instead of the latter does not change our results. Indeed, galaxies are distributed along the one-to-one line on the $(\sigma_{R_e/16}, \sigma_{R_e/2})$
### Table 5.2: Stellar kinematics and photometry

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Values of $\epsilon_{\text{kin}}$ and $PA_{\text{kin}}$ are taken from: (a) Scorza et al. (1998); (b) Lauer et al. (2005); (c) Bertola et al. (1992b); (d) Caldwell (1984b); (e) Franx et al. (1989b); (f) Fisher et al. (1994); (g) Peletier et al. (1990a); (h) Welch et al. (1991).
Figure 5.9: \( v/\sigma \) plotted against the ellipticity. Filled and open symbols represent galaxies with \( M(\text{H} \text{I}) \) above and below \( 10^8 \) \( M_\odot \) respectively. Light grey, dark grey and black symbols correspond to low-, intermediate- and high-\( \sigma \) galaxies respectively (see Sec. 2.2). The solid line represents the IOR model prediction (see text).

Finally, the ellipticity is \( \epsilon_{\text{RC}3} \), which is measured in the \( B \)-band at the 25\(^{th}\)-magnitude isophote by de Vaucouleurs et al. (1991). However, when the variation of the ellipticity with radius is published, we use the ellipticity \( \epsilon_{\text{kin}} \) at the radius of maximum rotation. This is more accurate if one wants to compare the observed galaxies to models on the \((\epsilon, v/\sigma)\) plane. Values of \( \epsilon_{\text{RC}3} \) and, when available, \( \epsilon_{\text{kin}} \) are given for all galaxies in Table 5.2. Clearly, in some galaxies \( \epsilon_{\text{kin}} \) is very different from \( \epsilon_{\text{RC}3} \) (e.g., NGC 3610, NGC 4026). In Table 5.2 we also list values of the major-axis position angle \( PA_{\text{kin}} \) measured at the same radius where \( \epsilon_{\text{kin}} \) is measured. \( PA_{\text{kin}} \) is equal to \( PA_{\text{RC}3} \) with the only exception of NGC 0596 and NGC 0636.

In Fig. 5.9 filled and open symbols represent galaxies with \( M(\text{H} \text{I}) \) above and below \( 10^8 \) \( M_\odot \) respectively, and the grey scale corresponds to the low-, intermediate- and high-\( \sigma \) bins defined in Sec. 2.2. The diagram in Fig. 5.9 has been used in now-classical studies to analyse the level of rotational support of bulges with respect to their flattening (pending uncertain inclination effects; e.g., Bertola & Capaccioli 1975; Illingworth 1977; Binney 1978). As usually done, we plot the theoretical edge-on isotropic oblate rotator (IOR) line using its analytical approximation \( (v/\sigma)_{\text{IOR}}=\sqrt{\epsilon/(1-\epsilon)} \) (e.g., Bender 1988). Classically, this has been used to measure the amount of anisotropy supporting ETG flattening. Points close to the line are close to the IOR case, points much below it might owe their flattening to anisotropy. As mentioned in Chapter 1, more recent works (Binney 2005; Cappellari et al. 2007) have emphasised that \( (v/\sigma)^*=(v/\sigma)/(v/\sigma)_{\text{IOR}} \) is not a good measure of anisotropy. In fact, galaxies with a higher value of \( (v/\sigma)^* \) seem to be more anisotropic. Given these developments, using \( (v/\sigma)^* \) has probably little meaning and we will not do it. Nevertheless, we keep the IOR curve in the diagram as a reference.

Fig. 5.9 shows quite some scatter and no clear trend. All points lay at or below the IOR curve. Consistent with the oblate anisotropic models of Cappellari et al. (2007), points avoid the large-\( \epsilon \), low-\( v/\sigma \) region. All three \( \sigma \)-groups populate the same region of the plot with the only exception that low-\( \sigma \) objects (light-grey circles) extend to higher \( v/\sigma \) values (a result known since the work of Davies et al. 1983). This is better appreciated in Fig. 5.10 where we plot \( v/\sigma \) against \( \sigma \) with the usual symbols.

With respect to the role of \( \text{H} \text{I} \), Figs. 5.9 and 5.10 suggest that at high \( \sigma \) (black symbols), \( \text{H} \text{I} \)-rich systems (filled circles) may have larger \( v/\sigma \) values than \( \text{H} \text{I} \)-poor ones.
5.3: Comparison to H I properties

Figure 5.10: $v/\sigma$ plotted against $\sigma$. Filled and open symbols represent galaxies with $M(\text{H I})$ above and below $10^8 M_\odot$ respectively. Light grey, dark grey and black symbols correspond to low-, intermediate- and high-$\sigma$ galaxies respectively (see Sec.2.2).

(open circles) despite having comparable ellipticity. This does not occur at low and intermediate $\sigma$ (in fact, the opposite is true at low $\sigma$ but, judging from the difference in $\epsilon$, this might just be an inclination effect).

To clarify this point we show in Fig.5.11 $v/\sigma$ and $\epsilon$ plotted against $M(\text{H I})$ and $\mu_{\text{HI}}$. The latter was defined in Chapter 2 as an empirical measurement of the settling level of an H I-gas distribution. Briefly, large $\mu_{\text{HI}}$ values correspond to extended, regularly rotating systems, and lower ones describe progressively less ordered gas distributions. Values of $\mu_{\text{HI}}$ are listed in Table 2.1. The left panels in Fig.5.11 show that the 4 galaxies with highest $v/\sigma$ (all in the low-$\sigma$ bin) are also the H I poorest ones and are highly flattened. However, many points are just upper limits on $M(\text{H I})$, so that the segregation of high-$v/\sigma$ and $-\epsilon$ galaxies at low-$M(\text{H I})$ is not significant. Furthermore, H I-rich galaxies have $v/\sigma$ values independent of $M(\text{H I})$. As mentioned above, high-$\sigma$ objects (black symbols) may represent an exception as they exhibit larger $v/\sigma$ at larger $M(\text{H I})$. However, a larger number of massive galaxies would be necessary to reach a firm conclusion. Finally, there may be a lack of $\epsilon \geq 0.4$-ETGs at large $M(\text{H I})$ values. It would be interesting to understand whether this effect is real or rather a bias in the sample.

We check on the right panel of Fig.5.11 whether $v/\sigma$ and $\epsilon$ depend on the particular H I morphology/kinematics by plotting them against $\mu_{\text{HI}}$. Again, no clear trend is visible. Overall, it seems that H I properties and stellar kinematics have little to do with each other. It is remarkable that extended H I discs can be found even around flattened slow rotators. For example, ESO 092-21, ESO 140-31 and NGC 5903 have low $v/\sigma$ with respect to their ellipticity, so that their shape is probably little supported by rotation. Nevertheless, they host large amounts of H I. While in ESO 140-31 and NGC 5903 the H I is likely distributed on polar, possibly disturbed structures, so that the lack of a stellar disc is not too surprising, in ESO 092-21 the H I is morphologically and kinematically aligned to the optical major axis, and the inner ionised gas seems to be rotating along with the H I. Yet, no kinematical signature of a corresponding stellar disc is found.

Along the same line, kinematical evidence of a stellar disc on top of a pressure-supported bulge is found both in galaxies with and without H I. For example, anti-correlated $v_{\text{star}}$ and $h_3$ are found in the IC 4889 and NGC 4278 (surrounded by regular H I distributions), NGC 2810 (partial H I ring), NGC 4472 (H I cloud), NGC 3610 and NGC 5322 (not detected in H I). The H I properties do not seem to be relevant in this respect.
5.3.2 Ionised-gas and H\textsc{i} kinematics

Analysing a sample of 12 SAURON galaxies, Morganti et al. (2006) were the first to address the connection between ionised-gas and H\textsc{i} velocity fields in ETGs. They found that whenever a galaxy hosts a settled, extended H\textsc{i} disc, bright ionised-gas is detected inside its stellar body; and that in these cases the velocity fields of outer-ionised-gas and inner-H\textsc{i} are contiguous. Keeping in mind the limitations of our long-slit data with respect to integral-field spectroscopy, but also taking advantage of the larger number of galaxies in our sample, we confirm this result.

Extended, relatively regular H\textsc{i} structures are detected in ESO 092-21, ESO 140-31, ESO 381-47, IC 4200, IC 4889, NGC 1947, NGC 2810, NGC 3108, NGC 3998, NGC 4026, NGC 4278, NGC 5173, NGC 5903. Ionised-gas is detected within the stellar body of all these galaxies. In most of the cases, its (large-radii) long-slit kinematics is consistent with that of the (innermost) H\textsc{i} gas (see Appendix 5.A for comments on individual galaxies).
In a few cases the connection is not clear because of either very faint ionised-gas emission (ESO 381-47 and NGC 5903), or because the ionised-gas kinematics is not obviously an inner extension of that of the H i (IC 4200 and NGC 2810). However, at least in the case of ESO 381-47 and NGC 2810, this may be due to the H i not being distributed regularly down to within the stellar body (see Figs 5.5 and 2.16). We stress that claiming such consistency between the kinematics of the ionised gas and that of the H i is as far as we can go with long-slit data. Integral-field spectroscopy is necessary if one wants to gain a more accurate understanding of the connection between the ionised and neutral gas-phase over an extended area of the sky rather than along a slit.

In Chapter 4 we show that, along with galaxies that are at the same time H i- and ionised-gas-rich, there are objects where the detection of a large mass of neutral gas does not correspond to that of bright, optical emission-lines. The just-mentioned ESO 381-47 is one of these galaxies. Other cases are NGC 1490 and NGC 5018. As for ESO 381-47, also in NGC 1490 and NGC 5018 the lack of ionised gas can be justified by the way the H i is distributed around the stellar body: in NGC 1490 the H i is detected on a few scattered clouds at 100-300 kpc from the stellar body; in NGC 5018 the H i is found on a long tail connecting two companion galaxies and stretching, in projection, across its stellar body. These cases strengthen the idea that a large $M(\text{H} \text{i})$ is not sufficient for a galaxy to host bright ionised-gas. It is also necessary that the H i is distributed on a relatively regular configuration extending to small radii; in which case, the kinematics of the ionised gas is consistent with that of the H i. Fainter H i detections confirm this conclusion as many of them have very irregular neutral hydrogen distributions and, at the same time, little or no ionised gas (NGC 4406, NGC 4472, NGC 7332, NGC 7619).

Finally, a few possible counter-examples exist. These are galaxies that, despite hosting cloud-like or irregular H i distributions, exhibit relatively bright and regularly-rotating ionised gas (NGC 2534, NGC 2768, and NGC 4125). However, it is not clear to what extent these objects contradict the general result. For example, NGC 2534 hosts H i spread over a large tail but also within the stellar body (see Fig 2.14). Given the low resolution of the H i observations of this galaxy, it is possible that the inner neutral hydrogen is regularly rotating on a disc or ring, providing a connection to the ionised-gas distribution. In NGC 2768, the ionised-gas kinematics towards the location of the H i cloud is consistent with the velocity of the cloud.

The conclusion is that, keeping in mind the limitations of our long-slit data, H i and ionised gas seem to be strongly related to each other. Only galaxies surrounded by regular H i distributions extending down to the stellar body host bright ionised-gas emission lines. And in almost all these cases the kinematics of the ionised gas is consistent with that of the H i. On the other hand, when little H i is detected or large masses of H i are not distributed all the way down to the stellar body, little ionised gas is found; and even in some of these cases the ionised-gas kinematics may be consistent with that of the H i.

### 5.4 Stellar kinematics and populations

In Chapter 4 we show that while the stellar age of ETGs is independent on $M(\text{H} \text{i})$, a large fraction of the H i-poor galaxies exhibits a significant stellar-age gradient with age decreasing towards the galaxy centre, in particular in objects with low and intermediate $\sigma$. Given the analysis presented in the present chapter, we can verify whether there is any
connection between such stellar-population properties and the stellar kinematics within our sample.

The top panels in Fig. 5.12 show the stellar age $t_{SSP}$ within the inner $R_e/16$ plotted against $v/\sigma$ and $\epsilon$. Galaxies with large rotational support are on average younger than slow rotators. However, this weak indication may be an effect of a bias in $\epsilon$, as highly flattened galaxies also tend to be younger within our sample (top-right panel). Furthermore, young objects are found at any $v/\sigma$ and $\epsilon$, so that no strong relation emerges. A larger number of high-$\epsilon$ galaxies would be needed to establish whether these are truly younger (on average) than rounder systems.

The bottom panels in Fig. 5.12 show the age variation when moving from the inner $R_e/2$ to the inner $R_e/16$ plotted against $v/\sigma$ and $\epsilon$. Again, no clear trend is observed, as centrally-rejuvenated galaxies ($\Delta \log_{10} t_{SSP} \leq -0.2$) are found at any $v/\sigma$ and $\epsilon$. Overall, it does not seem that the stellar populations of galaxies with different amount of rotational support are significantly different. The major caveat for this analysis is the poor sampling of the stellar body (in particular of the stellar kinematics) provided by long-slit
spectroscopic data.

Stellar age or age-variation within the optical body seem also to be independent on the occurrence of certain features in the stellar kinematics. For example, we find centrally-rejuvenated galaxies among those with a rising $\sigma_{\text{star}}$ profile (NGC 1439, NGC 2549) as well as among the objects with a $\sigma_{\text{star}}$ dip (NGC 7332) or plateau (e.g., NGC 207, NGC 7585). Similarly, all $\sigma_{\text{star}}$ profiles are represented among the uniformly-young galaxies. No clear relation is found also between stellar age and the $v_{\text{star}}$-$h_3$ anti-correlation. Among the galaxies exhibiting such anti-correlation we find centrally rejuvenated objects (e.g., NGC 4278), uniformly-young or intermediate-age systems (e.g., NGC 3610, IC 4889), and uniformly-old ones (e.g., NGC 4472). These results suggest that recent star formation is not in all cases a disc phenomenon.

Finally, KDC’s seem to avoid centrally rejuvenated or uniformly-young objects. Possible exceptions are NGC 1439 and NGC 5173, but better observations are needed to establish whether these objects harbour indeed a KDC. Generally, the stellar population of galaxies hosting a KDC is uniformly old (e.g., NGC 4406, NGC 4472), or of intermediate age (e.g., IC 4889, NGC 2434, NGC 5322). We also note that all galaxies hosting a KDC but IC 4889 have $v/\sigma \leq 0.3$. These results may fit with the finding that large KDC’s are usually old and reside within slow rotators (McDermid et al. 2006).

5.5 Summary

In this chapter we investigate the relation between the $\text{H} \ I$ properties of ETGs and the kinematics of stars and ionised gas within their stellar body. For this purpose we use the 21-cm interferometric data described in Chapter 2. For four galaxies in the sample we took new interferometric observations as part of this project. Observations of one of them are described in Chapter 3. We describe and analyse the observations of the remaining three objects in Sec.5.1. The $\text{H} \ I$ properties of these galaxies fall within the range discussed in Chapter 2. In particular, these are very $\text{H} \ I$-rich objects, with $M(\text{H} \ I)$ in the range $10^9-10^{10} \ M_\odot$. As often observed at such large $M(\text{H} \ I)$ values, the neutral gas is distributed over very extended, low-column-density structures exhibiting reasonably regular kinematics.

In the rest of the chapter we derive and analyse the kinematics of stars and ionised gas within the stellar body of galaxies in the sample. To do so we make use of the same long-slit optical spectra presented in Chapter 4 and there analysed to study stellar populations. In the present chapter, the kinematics of stars and ionised gas is derived by means of GANDALF. In agreement with previous work, we find a large variety of kinematical properties. ETGs can be rotating along the optical major or minor axis or not rotating at all, even when significantly flattened. The $\sigma_{\text{star}}$ profiles vary widely, going from raising ones to central plateau or even dips. Finally, most (but not all) galaxies with significant stellar rotation exhibit a $v_{\text{star}}$-$h_3$ anti-correlation, indicative of the presence of a rotating stellar disc on top of the underlying pressure-supported bulge.

The amount of rotational support to galaxy shape is investigated on the classical $v/\sigma$ vs. $\epsilon$ diagram. Galaxies in our sample occupy to usual region of the $(\epsilon,v/\sigma)$ plane. With respect to the $\text{H} \ I$ properties, we do not find any clear trend. $\text{H} \ I$-rich as well as $\text{H} \ I$-poor galaxies are found at any location on the diagram. There is no relation also with the morphology/kinematics of the $\text{H} \ I$ distribution. We find galaxies with regular $\text{H} \ I$ distributions but very little stellar rotation despite significant flattening. Finally,
kinematical signatures of a disc sub-component are not associated in any way with the detection or morphology of the H\textsuperscript{i}. Overall, the H\textsuperscript{i} seems to have little to do with the stellar kinematics of (the inner regions of) ETGs. Some stronger conclusions can be obtained studying the connection between ionised gas and H\textsuperscript{i}. It appears that galaxies surrounded by a regular H\textsuperscript{i} distribution extending all the way down to the stellar body host bright ionised-gas emission lines. Although long-slit spectroscopic data sample the kinematics of the ionised gas quite poorly, this is found to be at least consistent with that of the H\textsuperscript{i} in most of these cases. Certainly, if H\textsuperscript{i} and ionised gas were kinematically unrelated, we would have expected to find many more cases of clear inconsistency between their kinematics. In a few cases large masses of H\textsuperscript{i} are distributed so that no neutral gas is found close to the stellar body. In most of these galaxies little or no ionised gas is detected. Furthermore, H\textsuperscript{i}-poor systems are characterised by fainter or undetected emission lines within the stellar body. Even in a few of these cases the kinematics of the ionised gas is consistent with that of the H\textsuperscript{i}, while often it does not appear to be settled. We interpret these results as evidence that ionised-gas and H\textsuperscript{i} in ETGs are related and generally part of a same gaseous structure.

Finally, we find no strong relation between ETG stellar age or age gradient and stellar kinematics (e.g., $v/\sigma$, $\sigma_{\text{star}}$ profile). Most if not all KDC’s in our sample are hosted by uniformly old or intermediate-age, slow rotators.

Appendix 5.A Kinematics of individual galaxies

In what follows, we comment the stellar and ionised-gas kinematics of individual galaxies and the relation of these properties to the ones of the H\textsuperscript{i} gas (if detected). For the latter, we refer to Sec.2.3 unless stated otherwise. As in the main body of this chapter, we use the symbols $v_{\text{star}}$, $v_{\text{gas}}$, $\sigma_{\text{star}}$ and $\sigma_{\text{gas}}$ to refer to l.o.s. stellar velocity, ionised-gas velocity, stellar velocity dispersion and ionised-gas velocity dispersion respectively. The discussion below is based on the results of our analysis, which are shown in Fig.5.8. We refer to Sec.5.2.3 for a description of the figure. We specify for each galaxy the ellipticity $\epsilon_{\text{RC3}}$ and, when available, the major-axis position angle $P_{A\text{RC3}}$ that are listed in Table 5.2. No comments on the ionised gas kinematics are given if too few points are measured to derive any useful indication.

*ESO 092-21 ($\epsilon=0.24$, $PA=51$ deg)*

Stars – No stellar rotation is observed along any of the two axes despite the non-negligible flattening. Possibly, stars are rotating by a few km/s in the inner $\sim 5$ arcsec along $PA=48$ deg. If so, the $v_{\text{star}}$ gradient has opposite sign than that of $v_{\text{gas}}$. The $\sigma_{\text{star}}$ profile is basically flat along both axes. The $\sigma_{\text{star}}$ value measured within the easternmost bin along $PA=138$ deg ($\sigma_{\text{star}}\sim 30$ km/s) is too low, but values of $\sigma_{\text{star}}$ much below the instrumental dispersion (150 km/s) are not reliable and the fit quality is as in all the other bins.

Ionised gas – The gas is clearly rotating along $PA=48$ deg, with $v_{\text{gas}}$ increasing when moving eastwards. This is consistent with the H\textsuperscript{i} motion (see Fig.5.1 right panel). $v_{\text{gas}}$ may still be raising at the last measured points, where it has reached $\sim 100$ km/s. This is below the 145 km/s l.o.s.-rotation found for the neutral hydrogen along the same $PA$. However, since $v_{\text{gas}}$ has not flattened yet, this discrepancy does not rule out that ionised gas and H\textsuperscript{i} are part of one same structure. It is also possible that the hypothetical
circular orbits of the ionised gas are seen at slightly lower inclination than the H I disc, or that we are not sampling the kinematical major axis of the ionised gas.

**ESO 140-31 (ε=0.19, PA=74 deg)**

Stars – Stellar rotation of \(\sim 25 \text{ km/s}\) is observed along \(PA=81\) deg. The \(v_{\text{star}}\) gradient is steep in the inner 3 arcsec, where it tracks that of \(v_{\text{gas}}\), and drops to almost zero further out. Possibly, some residual rotation is visible along \(PA=171\) deg (also with a steeper inner \(v_{\text{star}}\) gradient and with sense of rotation consistent with that of the ionised gas). Along both axes, \(\sigma_{\text{star}}\) raises by \(\sim 30 \text{ km/s}\) when moving towards the centre, and then flattens onto a central plateau at \(\sim 150 \text{ km/s}\) in the inner \(\sim 5\) arcsec. \(h_3\) anti-correlates with \(v_{\text{star}}\) along \(PA=81\) deg.

Ionised gas – Along both axes, \(v_{\text{gas}}\) increases (in module) with radius within the inner 8 arcsec. However, along \(PA=81\) deg \(v_{\text{gas}}\) falls back to zero in the outer radial bins, while along \(PA=171\) deg it keeps raising to \(\sim 60 \text{ km/s}\). The outer gas rotation is consistent with the large-scale motion of the H I, which has kinematical major axis at \(PA=170\) deg (see Fig.5.4). However the latter reaches l.o.s. velocities \(\sim 3\) times higher.

**ESO 381-47 (ε=0.06)**

Stars – Along both axes the \(v_{\text{star}}\) gradient is very low. A stellar disc is visible in our optical imaging of this galaxy, but the l.o.s. rotation is only \(\sim 15 \text{ km/s}\). This may be due to the disc being nearly face on. \(\sigma_{\text{star}}\) increases mildly towards the centre of the galaxy, and possibly flattens in the inner 3 arcsec. Finally, along \(PA=177\) deg, \(h_3\) increases when moving northwards and anti-correlates with the weakly decreasing \(v_{\text{star}}\).

Ionised gas – Very little ionised gas is detected. \(v_{\text{gas}}\) is measured in too few points and at too low \(A/N\) to investigate whether the gas is moving in a coherent way. However, its motion along \(PA=177\) deg is consistent with that of the large-scale H I ring (see Fig.5.6), with velocities below systemic on the south side.

**IC 4200 (ε=0.37, PA=154 deg – see also Chapter 3)**

Stars – Stellar rotation is visible along \(PA=152\) deg. \(v_{\text{star}}\) is still rising at the last measured points, where it has reached \(\sim 130 \text{ km/s}\). No rotation is observed along \(PA=62\) deg, though our analysis in Chapter 3 suggests that an inner, weak KDC may be present. \(\sigma_{\text{star}}\) keeps raising all the way to the galaxy centre. No clear trend is observed in \(h_3\).

Ionised gas – \(v_{\text{gas}}\) gradients are observed along both \(PA\)'s. In particular, \(v_{\text{gas}}\) raises steeply to above \(100 \text{ km/s}\) along \(PA=62\) deg. It then starts falling back towards zero beyond the inner 8 arcsec. Along \(PA=152\) deg the situation is more complicated. The sign of the inner-2-arcsec \(v_{\text{gas}}\) gradient is opposite to that in the outer regions, where the ionised gas moves more consistently with the stars. The gas kinematics is hard to reconcile with coplanar circular motion. The sign of the \(v_{\text{gas}}\) gradient along \(PA=62\) deg is consistent with that of the H I motion. However, the connection between the two gas phases cannot be addressed with these data.

**IC 4889 (ε=0.35, PA=5 deg – see also discussion in Sec.5.3)**

Stars – Stellar rotation is observed along \(PA=0\) deg only. \(v_{\text{star}}\) is still raising at the last measured point where it has reached \(125 \text{ km/s}\). As already observed by previous authors (Carollo et al. 1993; Corsini et al. 2000), a KDC is clearly visible in the inner \(\sim 10\) arcsec and corresponds to a \(\sigma_{\text{star}}\) drop by \(\sim 30 \text{ km/s}\). Along \(PA=90\) deg, no rotation and a
nearly flat $\sigma_{\text{star}}$ profile are observed. $h_3$ is anti-correlated with $v_{\text{star}}$ along $PA=0$ deg, and its gradient changes sign at the KDC.

Ionised gas – Along $PA=0$ deg, the ionised-gas kinematics is consistent with and extends to outer radii the kinematics of the stellar KDC. The ionised gas is therefore counter-rotating with respect to the stars at large radii. Along $PA=90$ deg the gas is also kinematically decoupled from the stars in a way reminiscent of the situation in IC 4200 along $PA=62$ deg. The rotation raises sharply to above 140 km/s and then possibly starts falling back. These results are in very good agreement with the findings of Bertola et al. (1992a) and Corsini et al. (2000). Because the maximum $v_{\text{gas}}$ is similar along the two axes, assuming circular coplanar orbits the kinematical major axis of the ionised gas must be half a way between the two long-slit positions. This would be consistent with the kinematical major axis of the larger-scale H I, which has $PA\sim40$ deg. The sense of rotation would also be the same, with velocities below systemic being found on the north-east side. The main limitation in addressing this connection comes from the poor resolution of the H I data.

NGC 0596 ($\epsilon=0.25$, $PA=36$ deg)
Stars – Clear example of minor-axis rotator. A maximum stellar rotation of 80 km/s is observed along $PA=126$ deg, with the $v_{\text{star}}$ gradient varying with radius. $v_{\text{star}}$ seems to flatten after the inner 3-4 arcsec, but then possibly starts rising again. Along $PA=36$ deg there is weak stellar rotation in the inner few arcsec corresponding to a central $\sigma_{\text{star}}$ dip. $\sigma_{\text{star}}$ flattens also in the central region along $PA=126$ deg. Finally, $h_3$ increases (anti-correlating with $v_{\text{star}}$) when moving eastwards along $PA=126$ deg.

NGC 0636 ($\epsilon=0.15$, $PA=5$ deg)
Stars – Most of the stellar rotation is observed along the RC3 minor axis ($PA=96$ deg), where $v_{\text{star}}$ reaches 60 km/s. However, as mentioned above, the major axis is found at $PA\sim90$ deg in the inner regions (Rembold et al. 2002; Franx et al. 1989b). Therefore, the galaxy is not a minor-axis rotator. Some rotation is detected also along $PA=6$ deg (22 km/s). $\sigma_{\text{star}}$ raises by $\sim30$ km/s towards the centre. These results are consistent with the plots shown in Franx et al. (1989a). Along $PA=96$ deg $h_3$ is anti-correlated with $v_{\text{star}}$.

NGC 1426 ($\epsilon=0.30$, $PA=103$ deg)
Stars – Rotation is found along $PA=109$ deg, with the inner steeply-raising rotation curve flattening at 2-3 arcsec from the centre to $v_{\text{star}}=96$ km/s. No rotation is observable along $PA=19$ deg, but a weak central dip in $\sigma_{\text{star}}$ is found. The dip might be missed along $PA=109$ deg because of different slit centring. $h_3$ along $PA=109$ deg is anti-correlated with $v_{\text{star}}$ in the central 15 arcsec. Simien & Prugniel (1997) show stellar kinematics of NGC 0636 along $PA=103$ deg. They find stellar rotation of $\sim100$ km/s within the inner 20 arcsec. However, their $v_{\text{star}}$ curve raises less steeply than ours. This may be due to an offset in the slit centring, with our slit being closer to the line of nodes.

NGC 1439 ($\epsilon=0.27$, $PA=45$ deg)
Stars – For this galaxy the systemic velocity is at $v_{\text{star}}\sim20$ km/s. Along $PA=28$ deg, a steep central raise is followed by a gentle decrease towards systemic on the east side, and by flattening and sharp decrease on the west side. Overall, the impression is of a
rather complicated velocity structure possibly hosting a KDC. Along $PA=118$ deg the rotational velocity rises near the centre, then decreases and then rises again at the last few points. Along both axes $\sigma_{\text{star}}$ peaks at the galaxy centre and $h_3$ is anti-correlated with $v_{\text{star}}$. Our $v_{\text{star}}$ and $\sigma_{\text{star}}$ curves are in agreement with those shown in [Franx et al. (1999a)]. In particular, they also find that $v_{\text{star}}$ peaks at larger radius on the west side of the galaxy, and that $\sigma_{\text{star}}$ raises to $\sim150$ km/s towards the centre.

**NGC 1490 ($\epsilon=0.14$, $PA=131$ deg)**

Stars – 140-km/s stellar rotation is detected along $PA=145$ deg, with $v_{\text{star}}$ flattening at 4-6 arcsec from the galaxy centre. Residual rotation of $\sim30$ km/s is seen along $PA=55$ deg. Along both axes, $\sigma_{\text{star}}$ raises by 100 km/s when moving from a radius of 10 arcsec to the galaxy centre. Finally, $h_3$ anti-correlates with $v_{\text{star}}$ along $PA=145$ deg, and $h_4$ decreases towards the centre along both axes.

**NGC 1947 ($\epsilon=0.08$, $PA=40$ deg)**

Stars – Stellar rotation is mostly seen along $PA=5$ deg, where it rises quickly and then flattens at $v_{\text{star}}=45$ km/s. Some residual stellar rotation is observed along $PA=95$ deg. The $\sigma_{\text{star}}$ profile is flat. Our results are consistent with those of [Carollo et al. (1993)] along similar $PA$’s.

Ionised gas – Rotation is observed along both $PA$’s. In particular, a regular rotation curve flattening to $v_{\text{gas}}=200$ km/s is observed along $PA=95$ deg (where the stars are hardly rotating). This motion is consistent with the one of the H I. Along $PA=5$ deg, the gas seems to follow the central stellar rotation and extends it to larger radii. Overall, the two $v_{\text{gas}}$ curves are consistent with the ionised gas being coplanar with the dust lane and inner H I gas ($PA\sim130$ deg). Indeed, if this were the case, we would not be seeing the full ionised-gas rotation along $PA=95$ deg, and we should still see some rotation along $PA=5$ deg.

**NGC 2300 ($\epsilon=0.23$, $PA=73$ deg)**

Stars – This is another case of minor-axis rotator. A steeply-raising rotation curve is observed along $PA=164$ deg. The curve is still rising at the last measured point, where $v_{\text{star}}=30$ km/s. Some rotation is detected also along $PA=74$ deg and only in the inner 4-5 arcsec. The $\sigma_{\text{star}}$ profile raises towards the centre. As shown in Fig 5.8, these results are consistent with those of [Bender et al. (1994)] along similar $PA$’s.

**NGC 2434 ($\epsilon=0.10$, $PA=135$ deg)**

Stars – Little stellar rotation is detected along both axes. Along $PA=132$ deg, the kinematics in the centre is possibly misaligned with respect to the outer one. The $\sigma_{\text{star}}$ profile raises towards the centre along both axes. These results are in very good agreement with previous work by [Carollo & Danziger (1994b)]. $h_3$ anti-correlates with $v_{\text{star}}$ along $PA=132$ deg.

Ionised gas – Little ionised gas is detected and at low $A/N$. The gas seems to be rotating along $PA=42$ deg, while it shows highly anomalous velocities along $PA=132$ deg. Deeper data would be more appropriate to assess the significance of this result, but one must consider that more galaxies show such peculiar (possibly unsettled?) gas motion, in particular when the emission is faint (e.g., NGC 7332 below and in [Sarzi et al. 2006]).
NGC 2534 ($\epsilon=0.02$)
Stars – The galaxy is basically round. Nevertheless, some rotation is observed along both axes. The $\sigma_{\text{star}}$ profile is basically flat and $h_3$ anti-correlates with $v_{\text{star}}$.
Ionised gas – Rotation is detected along both axes and is consistent with the stellar kinematics along $PA=135$ deg. On the other hand, it is decoupled from it along $PA=45$ deg. Along the latter, the gas reaches on the east side a velocity 100 km/s higher than on the west side. The $\text{H} \, \text{I}$ rotation is not spatially resolved in the centre of the galaxy. Therefore, more accurate $\text{H} \, \text{I}$ observations would be needed to determine the relation between $\text{H} \, \text{I}$ and ionised gas. However, the ionised gas kinematics along $PA=135$ deg is not consistent with the one of the $\text{H} \, \text{I}$ tail, which has velocity lower than systemic on the west side of the galaxy (see Fig.2.14).

NGC 2549 ($\epsilon=0.62$, $PA=178$ deg)
Stars – Stellar rotation is observed along $PA=1$ deg, where $v_{\text{star}}$ flattens to 130 km/s at $\sim8$ arcsec from the centre. No rotation is observable along $PA=91$ deg. The $\sigma_{\text{star}}$ profile raises up to $\sim150$ km/s in the centre. $h_3$ anti-correlates with $v_{\text{star}}$ along $PA=1$ deg. Fig.5.8 shows that all our findings are consistent with SAURON observations of this galaxy.

NGC 2768 ($\epsilon=0.60$, $PA=92$ deg)
Stars – $v_{\text{star}}$ reaches 94 km/s along $PA=95$ deg but has not flattened yet at the last measured point. No stellar rotation is measured along $PA=5$ deg, where $v_{\text{star}}$ shows a central 40 km/s dip which could be caused by poor slit centring. $\sigma_{\text{star}}$ drops by $\sim50$ km/s in the centre along both axes. $h_3$ may be anti-correlated with $v_{\text{star}}$ along $PA=95$ deg. As discussed in Sec.5.2.4, these findings are in agreement with the SAURON LOSVD maps with the exception of a $\sim0.05$-offset in $h_4$. The central $v_{\text{star}}$ dip along $PA=5$ deg is also reproduced by placing an off-centre slit on top of the SAURON velocity field.
Ionised gas – $v_{\text{gas}}$ raises sharply to 200 km/s within the inner few arcsec along $PA=185$ deg. We note that the northern-emission velocity is $\sim200$ km/s larger than systemic, so that it may be consistent with that of the northern $\text{H} \, \text{I}$ cloud (see Chapter 2). The ionised gas detections are weaker along $PA=95$ deg, but the gas seems to be counter-rotating with respect to the stars. These findings are consistent with SAURON Sarzi et al. (2006) velocity fields.

NGC 2810 ($\epsilon=0.16$)
Stars – $v_{\text{star}}$ raises smoothly to 124 km/s along $PA=135$ deg, possibly flattening at the outer measured points. No or little stellar rotation is found along $PA=45$ deg. $\sigma_{\text{star}}$ increases towards the centre along both axes. $h_3$ is anti-correlated with $v_{\text{star}}$ and $h_4$ decreases towards the centre along $PA=135$ deg.
Ionised gas – Also in this galaxy ionised gas and stars are kinematically decoupled. $v_{\text{gas}}$ raises to $\sim80$ km/s along $PA=45$ deg. Along $PA=135$ deg, it follows the central raising part of the stellar-velocity curve and then falls back to zero. This is not consistent with the larger-scale $\text{H} \, \text{I}$ kinematics, which has velocities below systemic on the north-west side along $PA=135$ deg (see Fig.2.16). However, no $\text{H} \, \text{I}$ is seen within the stellar body of the galaxy, so that the connection between the two gas phases is not easy to understand. The galaxy is among the ionised-gas-richest of the sample (see Table 4.3) and one might
think that the ionised gas is filling the central H\textsc{i} hole. Note that NGC 2810 is a radio-excess galaxy (Drake et al. 2003) so that a central AGN may be relevant for ionising the inner gas.

**NGC 2904** ($\epsilon=0.38$, $PA=90$ deg)

Stars – $v_{\text{star}}$ raises to 106 km/s along $PA=90$ deg and possibly flattens at 8 arcsec from the centre. No rotation is observed along $PA=178$ deg. $\sigma_{\text{star}}$ varies little with radius along both axes. $h_3$ clearly anti-correlates with $v_{\text{star}}$ along $PA=90$ deg.

**NGC 3108** ($\epsilon=0.20$, $PA=50$ deg)

Stars – Stellar rotation is measured along $PA=45$ deg and seems to flatten to 78 km/s at 6-8 arcsec from the centre. No rotation is observed along $PA=135$ deg. Along both axes $\sigma_{\text{star}}$ is basically flat. $h_3$ exhibits an unusual central peak along $PA=45$ deg, while $h_4$ decreases towards the centre along the perpendicular axis. Carollo et al. (1993) long-slit spectra were taken along $PA=0$ and 90 deg and therefore the $v_{\text{star}}$ profiles are not comparable. Ionised gas – Gas is most clearly detected along $PA=135$ deg, where $v_{\text{gas}}$ reaches 200 km/s on the east side and almost 300 km/s on the west side. Such fast rotation is consistent with the H\textsc{i} motion (see Fig. 2.17), as discussed in Oosterloo et al. (2002). The ionised gas may be filling the central H\textsc{i} hole. Little gas is detected along $PA=45$ deg and its kinematics is not clear.

**NGC 3193** ($\epsilon=0.12$)

Stars – Rotation of 69 km/s is detected along $PA=0$ deg. $v_{\text{star}}$ flattens at $\sim3$ arcsec from the centre. Along $PA=90$ deg stars are not rotating. $\sigma_{\text{star}}$ exhibits a slight increase towards the centre along both axes. Fig. 5.8 shows that these results are in agreement with those of BSG94. $h_3$ anti-correlates with $v_{\text{star}}$ along $PA=0$ deg. Ionised gas – Detections are at very low level in all the bins where some gas is found. Along $PA=0$ deg, $v_{\text{gas}}$ seems to be tracking $v_{\text{star}}$, while no coherent pattern can be derived along $PA=90$ deg.

**NGC 3610** ($\epsilon=0.24$, $PA=51$ deg)

Stars – $v_{\text{star}}$ raises sharply to 157 km/s and then flattens at $\sim125$ km/s along $PA=130$ deg. The $v_{\text{star}}$ curve is in good agreement with BSG04 result. Small differences could be due to a difference in the slit position. Along $PA=40$ deg, we observe a central dip of $\sim70$ km/s in $v_{\text{star}}$. This could be due to poor slit centring combined with the large $v_{\text{star}}$ gradient along the perpendicular direction. No such dip is observed by BSG94. Both axes show a central $\sigma_{\text{star}}$ dip which is very broad and off-centre along $PA=130$ deg. This is in agreement with BSG94 result along $PA=40$ deg but not along $PA=130$ deg. The reason for this discrepancy is not clear. However, the observation and lack of a $\sigma_{\text{star}}$ dip in BSG94 data along $PA=40$ and 130 deg respectively, suggests some centring problems (also) in their observations. $h_3$ anti-correlates with $v_{\text{star}}$ along $PA=130$ deg.

**NGC 3640** ($\epsilon=0.23$, $PA=92$ deg)

Stars – Stellar rotation is observed along $PA=90$ deg. $v_{\text{star}}$ is still raising at the last measured points, where it amounts to 100 km/s. No rotation is measured along $PA=180$ deg. The velocity dispersion profile is nearly flat. These results confirm earlier BSG94 findings. No $h_3$-$v_{\text{star}}$ anti-correlation is observed despite the clear stellar rotation.
NGC 3998 ($\epsilon=0.16$, PA=138 deg)
Stars – Stellar rotation is clearly detected along PA=140, where the three most central bins are poorly fitted and should be neglected. The unsuccessful fit may be caused by the contamination from AGN emission. NGC 3998 is known to be an AGN (e.g., Heckman 1980) and belongs to the Drake et al. (2003) radio-excess galaxy sample. Regarding the outer bins, $v_{\text{star}}$ is still raising at the last measured point, where it has reached 167 km/s. This is consistent with previous Fisher (1997) results. Along PA=50 deg, we see a central dip in $v_{\text{star}}$ possibly caused by poor slit centring. $\sigma_{\text{star}}$ raises to $\sim300$ km/s towards the centre along both axes (neglecting the poorly-fitted bins). This result is also in agreement with the observations of Fisher (1997). No clear trend is observed in $h_3$.
Ionised gas – The gas motion seems consistent with that of the stars along PA=140 deg, confirming Fisher (1997) findings. On the other end, the gas is decoupled from the stars along PA=50 deg, where $v_{\text{gas}}$ raises up to $\sim150$ km/s. This is consistent with (although slower than) the H I-ring kinematics.

NGC 4026 ($\epsilon=0.40$, PA=1 deg)
Stars – 163-km/s stellar rotation is found along PA=178 deg and may keep raising beyond the last measured point. $v_{\text{star}}$ is zero everywhere along PA=88 deg. $\sigma_{\text{star}}$ raises sharply towards the centre. $h_3$ is found to be unusually correlated with $v_{\text{star}}$ along PA=178 deg at large radii. All these findings are consistent with those of Fisher (1997).
Ionised gas – As found by Fisher (1997), $v_{\text{gas}}$ tracks very closely $v_{\text{star}}$ along PA=178 deg. Both stellar and ionised gas rotation is in good agreement with the kinematics of the H I ring. It is possible that the ionised gas is filling the central H I hole.

NGC 4125 ($\epsilon=0.22$, PA=95 deg)
Stars – 149-km/s stellar rotation is observed along PA=80 deg. The rotation is still rising at the last measured point. Stars are not rotating along PA=170. Along both axes $\sigma$ falls by 40-50 km/s in the centre. As shown in Fig.5.8, these results are in agreement with those of BSG94 along PA=82 deg. No clear relation is observed between $v_{\text{star}}$ and $h_3$.
Ionised gas – Along PA=80 deg, $v_{\text{gas}}$ raises more steeply than $v_{\text{star}}$, but is then not detected beyond a radius of 10 arcsec. $A/N$ is low along PA=170 deg and no coherent picture can be derived.

NGC 4278 ($\epsilon=0.18$, PA=16 deg)
Stars – Stellar rotation is observed along PA=20 deg, flattening after the inner $\sim10$ arcsec to $\sim80$ km/s and maybe falling off beyond 15 arcsec from the centre. Little residual stellar rotation is detected along PA=110 deg. $\sigma_{\text{star}}$ raises when moving towards the centre along both axes. $h_3$ is anti-correlated with $v_{\text{star}}$ along PA=20 deg. Our results are in excellent agreement with those of Emsellem et al. (2004) derived from SAURON integral-field spectroscopy.
Ionised gas – Along PA=20 deg, the rotation of the gas is consistent with that of the stars, but significantly faster. $v_{\text{gas}}$ flattens at $\sim200$ km/s outside the inner 5-6 arcsec. Possibly, it falls back to zero on the west side. Along PA=110 deg, the ionised gas is weakly counter-rotating with respect to the stars in the inner few arcsec. This motion is in agreement with the large-scale H I kinematics and argues for H I and H II belonging to a same structure (see the discussion in Morganti et al. 2006). Our results are consistent with the ionised-gas velocity fields presented in Sarzi et al. (2006).
NGC 4406 ($\epsilon=0.18$, $PA=50$ deg)
Stars – This is a known stellar KDC (Franx et al. 1989a; BSG94). Along $PA=120$ deg, $v_{\text{star}}$ raises sharply to 68 km/s in the inner $\sim 5$ arcsec, and declines back to zero at larger radii. Our result is in quantitative agreement with that of BSG94 (see Fig 5.8). Along $PA=30$ deg a 24-km/s stellar rotation is observed. The central $v_{\text{star}}$ peak can be justified with a slightly off-centre slit position combined to the large $v_{\text{star}}$ gradient along the perpendicular direction. $\sigma_{\text{star}}$ raises sharply by $\sim 60$ km/s when moving towards the centre. $h_3$ anti-correlates with $v_{\text{star}}$ along both axes. In particular, it traces the central KDC along $PA=120$ deg.

NGC 4472 ($\epsilon=0.17$, $PA=160$ deg)
Stars – Stellar rotation of 60 km/s is observed along $PA=155$ deg. Along the same axis, the central few arcsec do not show rotation along the line of sight and correspond to a $\sigma_{\text{star}}$ dip. Along $PA=65$ deg, no stellar rotation is observed and $\sigma_{\text{star}}$ varies little. These results are in good agreement with those of BSG94 (see Fig 5.8). $h_3$ anti-correlates with $v_{\text{star}}$ along $PA=155$ deg, including the central, kinematically-decoupled region.

NGC 5018 ($\epsilon=0.32$, $PA=93$ deg)
Stars – 58-km/s stellar rotation is detected along $PA=95$ deg, while a strong, $\sim 100$-km/s $v_{\text{star}}$ central peak is found along $PA=185$ deg. This peak cannot be explained with an off-centre slit position. The reason is that its height is too close to the width of the $v_{\text{star}}$ range covered along the perpendicular direction, and the latter does not exhibit a steep $v_{\text{star}}$ gradient. This feature is not visible in the data of Carollo & Danziger (1994a) along the same $PA$. On the other hand, our result along $PA=95$ deg is in agreement with this previous work and with that of Longhetti et al. (1998). Along $PA=95$ deg, a $\sigma_{\text{star}}$ dip corresponds to the steeper part of the rotation curve as in Carollo & Danziger (1994a). $\sigma_{\text{star}}$ remains constant with radius along $PA=5$ deg. $h_3$ is anti-correlated with $v_{\text{star}}$. The anomalous LOSVD of this galaxy along $PA=5$ deg could be related to its being morphologically strongly disturbed (e.g., Buson et al. 2004).

NGC 5173 ($\epsilon=0.14$)
Stars – Stellar rotation is detected along $PA=105$ deg, where $v_{\text{star}}$ possibly flattens at $\sim 30$ km/s after about 8 arcsec from the centre. No rotation is found at $PA=15$ deg, but a $v_{\text{star}}$ central dip may be caused by poor slit centring. A small $\sigma_{\text{star}}$ dip is detected along $PA=105$ deg, while $\sigma_{\text{star}}$ raises towards the centre along the perpendicular axis. $h_3$ anti-correlates with $v_{\text{star}}$ along both axes.

Ionised gas – Along $PA=105$ deg, the ionised gas is kinematically decoupled from the stars. $v_{\text{gas}}$ and $v_{\text{star}}$ show gradients with opposite signs. The projected gas rotation is larger than that of the stars, and reaches $\sim 100$ km/s. Such motion is consistent with the $\text{H} \, \text{I}$ velocity gradient along the same $PA$ (see Chapter 2). Along $PA=15$ deg, ionised gas and stars seem to share the same l.o.s. velocity.

NGC 5322 ($\epsilon=0.38$, $PA=95$ deg)
Stars – Along $PA=95$ deg, we observe a rotating KDC as opposed to the outer lack of rotation. $v_{\text{star}}$ along the KDC raises steeply up to 83 km/s. This result is in excellent agreement with that of BSG94. Such sharp $v_{\text{star}}$ gradient and bad slit centring could explain the $v_{\text{star}}$ dip along $PA=5$ deg (not observed by BSG94). Along this axis, an
overall velocity gradient is observed spanning a 40 km/s velocity range. Therefore, while inner rotation is detected along \(PA=95\) deg, at outer radii stars may be rotating along \(PA=185\) deg.

**NGC 5903 (\(\epsilon=0.26, \ PA=164\) deg)**

Stars – No stellar rotation is found along either axes. \(\sigma_{\text{star}}\) raises when approaching the galaxy centre. These results are consistent with those of Carollo et al. (1993).

Ionised gas – Despite the low-level detections, the gas seems to be rotating along \(PA=165\) deg while not much can be said about the perpendicular axis. We note that the \(v_{\text{gas}}\) gradient along \(PA=165\) deg is opposite to what expected if the ionised gas were somehow connected to the north-south \(\text{H} \ I\) filamentary structure. The lack of bright ionised-gas emission along \(PA=75\) deg does not allow to establish the connection to the \(\text{H} \ I\) directly associated to the galaxy (see Chapter 2).

**NGC 7052 (\(\epsilon=0.50, \ PA=66\) deg)**

Stars – Stellar rotation is observed along \(PA=67\) deg, where \(v_{\text{star}}\) reaches 105 km/s within the inner 5 arcsec and then flattens to 80-90 km/s outwards. No stellar rotation is detected along \(PA=157\) deg. \(\sigma_{\text{star}}\) has a flat profile along both axes. \(h_3\) anti-correlates with \(v_{\text{star}}\) along \(PA=67\) deg.

Ionised gas – Gas is detected in the inner 4-5 arcsec of the galaxy and rotates along \(PA=67\) deg with a steeper rotation-curve than the stars, reaching above 200 km/s. The gas stays at \(v_{\text{gas}}\sim0\) along \(PA=157\) deg. The galaxy is a known AGN and it is possible that the gas is ionised mostly in the inner region because of the nuclear activity.

**NGC 7332 (\(\epsilon=0.72, \ PA=154\) deg)**

Stars – \(v_{\text{star}}\) along \(PA=160\) deg is still rising or possibly just beginning to flatten at the last measured points, where it is of 143 km/s. A weak, \(\sim20\) km/s \(\sigma\) dip is detected in the centre along the same \(PA\). No rotation is measured along \(PA=70\) deg, where \(\sigma_{\text{star}}\) raises towards the centre. Along \(PA=160\) deg, \(h_3\) seems be anti-correlated with \(v_{\text{star}}\) within the inner 20 arcsec, and correlated with it outside this range. All these results are in excellent agreement with those of Emsellem et al. (2004; see also Falcón-Barroso et al. 2004): the dashed lines representing SAURON observations in Fig. 5.8 are barely visible behind our data.

Ionised gas – Gas is detected at low level and does not seem to be moving in an ordered way. The general impression is of anomalous, higher-than-systemic velocity along both axes. Our results for the ionised-gas kinematics are consistent with SAURON observations of this object. As discussed by Morganti et al. (2006), the ionised-gas velocity is not consistent with that of the \(\text{H} \ I\) cloud detected \(\sim14\) kpc from the stellar body.

**NGC 7457 (\(\epsilon=0.45, \ PA=127\) deg)**

Stars – This is another clear flattened major-axis rotator. \(v_{\text{star}}\) raises smoothly to 70 km/s along \(PA=128\) deg and is still raising at the last measured point. No rotation is observed along the perpendicular axis, where a small \(v_{\text{star}}\) central peak is maybe due to an off-centre slit position. \(\sigma_{\text{star}}\) is a factor of 2 below the instrumental dispersion, and has a roughly flat profile along both axes. No \(v_{\text{star}}h_3\) anti-correlation is observed. Our results are in excellent agreement with SAURON observations (with the exception of one poor fit). The slight offset in \(\sigma_{\text{star}}\) along \(PA=128\) deg is not worrying given that we are well below the instrumental dispersion.
NGC 7585 (ϵ=0.20, PA=94 deg)
Stars – Little stellar rotation is detected and $\sigma_{\text{star}}$ has a flat profile along both axes. $h_4$ exhibits a central dip along $PA=17$ deg.
Ionised gas – Tentatively, the gas is rotating along $PA=107$ deg, but all detections are at a low level and the $v_{\text{gas}}$ seems shifted with respect to the stellar systemic velocity. The gas may be unsettled.

NGC 7600 (ϵ=0.52, PA=58 deg)
Stars – Stellar rotation is observed along $PA=68$ deg, where $v_{\text{star}}$ reaches 73 km/s and possibly flattens at 8 arcsec from the centre. This result is in qualitative agreement with observations by Dressler & Sandage (1983). No rotation is measured along the perpendicular axis. $\sigma_{\text{star}}$ has a nearly flat profile. $h_3$ is anti-correlated with $v_{\text{star}}$ along $PA=68$ deg.

NGC 7619 (ϵ=0.30, PA=25 deg)
Stars – Stars rotate along $PA=35$ deg, where $v_{\text{star}}$ raises sharply to 71 km/s and flattens after the inner 5 arcsec. No rotation is observed along $PA=125$ deg. The $\sigma_{\text{star}}$ profile is a steeply-raising one along both axes. Our results are in good agreement with those of Franx et al. (1989a). $h_3$ anti-correlates with $v_{\text{star}}$ along $PA=35$ deg.

NGC 7626 (ϵ=0.12, PA=20 deg)
Stars – No coherent stellar rotation is observed along either axes. $v_{\text{star}}$ is zero within a large scatter. Possibly, rotation is visible in inner 3 arcsec along $PA=21$ deg, as observed also by Longhetti et al. (1998). As in that work, the $\sigma_{\text{star}}$ profile is flat.