Structure and kinematics of edge-on galaxy disks
Kregel, Michiel

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The Neutral Hydrogen of Edge-on Spiral Galaxies

M. Kregel, P. C. van der Kruit & W. J. G. de Blok

ABSTRACT — We present Australian Telescope Compact Array (ATCA) and Westerbork Synthesis Radio Telescope (WSRT) H I synthesis observations of 15 edge-on spiral galaxies of intermediate to late morphological type. The global properties and the distribution and kinematics of the H I gas are derived and discussed. We point out that the envelope-tracing method for determining the rotation curve is unreliable in the inner parts, where the effects of beam smearing and the line-of-sight projection are most pronounced.

5.1 Introduction

The neutral atomic hydrogen gas (H I) in spiral galaxies is highly dissipated, its bulk being confined to nearly circular orbits and forming a thin layer in the galaxy plane. This physical property makes the H I 21-cm emission line an excellent tracer of the circular speed curves of spiral galaxies, and hence of their underlying radial mass distributions (Bosma 1978; Beigman 1987; de Blok, McGaugh, & van der Hulst 1996). This also applies to the H I in spirals that are viewed edge-on, albeit that the velocity profiles are more complex due to the line-of-sight (l.o.s.) projection (Sancisi & Allen 1979; Sofue 1996; García-Ruiz, Sancisi, & Kuijken 2002). Although challenging, the l.o.s. projection in edge-on spirals is actually much less severe for the H I layer than for the old stellar disk (Ch. 4). From a practical viewpoint, the signal-to-noise of H I synthesis observations is generally larger such that the H I can be studied at a higher velocity resolution. From the physical side, the H I velocity dispersion is typically 6–13 km s$^{-1}$ (van der Kruit & Shostak 1982; Kamphuis 1993), much smaller than that of the old stellar population. Hence, the H I l.o.s. velocity profiles are mainly shaped by the density distribution and the rotation curve. The H I rotation curves of edge-on spirals may therefore be retrieved from the extreme-velocity envelope of the major axis position-velocity (XV) diagram.

In Ch. 4 we presented deep optical long-slit spectra for 17 edge-on spirals and extracted the l.o.s. stellar kinematics. A determination of the H I rotation curves of these edge-on spirals
gives the additional constraint needed to build realistic dynamical models of their stellar disks (Ch. 7). This will allow a study of the intrinsic stellar disk velocity dispersion and the stellar disk surface density. Previously, HI synthesis observations were made only for three galaxies in this sample: NGC 891 (Sancisi & Allen 1979; Rupen 1991; Swaters, Sancisi, & van der Hulst 1997), NGC 5170 (Bottema, van der Kruit, & Freeman 1987) and NGC 5529 (Rhee & van Albada 1996). Here, we present both new 21-cm synthesis radio observations for 14 galaxies, including more sensitive observations of NGC 5170 and NGC 5529, and archival observations for 4 additional galaxies. The prime purpose of these HI observations is to provide detailed rotation curves. Besides allowing the construction of dynamical models of the stellar disks, these HI rotation curves can also be compared to the optical emission line velocities, yielding an estimate of the effect of dust extinction on the observed stellar kinematics (Ch. 6). In addition, the morphology of the HI can be used to gauge environmental influences through the presence of telltale signs such as warping of the HI layer and the presence of companions.

The outline of this chapter is as follows. In Sect. 5.2 the HI synthesis observations are presented and the reduction steps are summarized. The continuum and HI emission is analyzed in Sect. 5.3. This section also contains a brief investigation of the envelope-tracing method for determining the HI rotation curves. In Sect. 5.4 we explore the global HI properties of this sample of edge-on spirals. Finally, a summary is presented in Sect. 5.5. Throughout distances are calculated using the Virgo-centric velocities from the Lyon/Meudon Extragalactic Database (LEDA, see Table 2.1) and a Hubble constant \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

5.2 Observations and Data Reduction

5.2.1 New observations

The main observational parameters of both the new and the archival observations (Sect. 5.2.2) are given in Table 5.1. Among the fourteen newly targeted galaxies, we decided to re-observe NGC 5170 and NGC 5529, because earlier observations lacked the sensitivity to determine their rotation curves. The new 21-cm line observations were carried out during 2000–2001 using the ATCA and the WSRT. The new ATCA observations were performed with the array in one of its 1.5 km configurations (Table 5.1) and using the correlator configured to cover a bandwidth of 8 MHz with 1024 channels (1.6 km s\(^{-1}\) channel\(^{-1}\)). On-line Hanning velocity smoothing was not applied. To calibrate the flux density scale and the bandpass the source PKS B1934-638 was observed for 15 minutes at either the start or the end of each full synthesis observation. To allow proper correction of gain and phase changes the galaxy observations were interspersed every hour with a 5 minute observation of a secondary calibrator.

Note that for three of the galaxies (ESO 263-G15, ESO 321-G10 and ESO 435-G50) the quality of the recorded optical spectra (Ch. 4) proved too low to determine their stellar kinematics. Their HI content does still contain valuable information and is included here.

The WSRT observations of NGC 5529 were carried out using the ‘Maxi-Short’ configuration. This configuration yields 52 baselines, the shortest being 36m, 54m, 72m and 90m. The correlator provided 128 channels over a 10MHz bandwidth (16.6 km s\(^{-1}\) channel\(^{-1}\)). On-line velocity tapering was not applied in order to retain the highest possible velocity resolution. Initial calibration was performed using the sources 3C147 and CTD93, after which a self-calibration procedure on the continuum map of the field surrounding NGC 5529 was used to perfect the calibration.
Table 5.1: Observing parameters

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ESO142-G24</td>
<td>8 Mar 1997</td>
<td>01:50 02:45</td>
<td>8h 30m</td>
<td>32° 57' 20&quot;</td>
<td>18.5</td>
<td>15.0</td>
<td>70%</td>
</tr>
<tr>
<td>ESO157-G181</td>
<td>11 Jun 2001</td>
<td>01:30 02:45</td>
<td>10h 30m</td>
<td>12° 00' 00&quot;</td>
<td>20.0</td>
<td>17.5</td>
<td>80%</td>
</tr>
<tr>
<td>ESO201-G22</td>
<td>16 Sep 2000</td>
<td>01:30 02:45</td>
<td>8h 30m</td>
<td>45° 00' 00&quot;</td>
<td>15.0</td>
<td>12.5</td>
<td>90%</td>
</tr>
</tbody>
</table>

Notes - Columns: (1) Name, an asterisk indicates archival data; (2) Observing date; (3) Observing time; (4) Pointing center; (5) Central velocity; (6) Array configuration; (7) Full-resolution synthesized beam; (8) Root-mean-square (r.m.s.) noise in the full-resolution channel maps; (9) HI mass corresponding to a 50 km/s peak source at the adopted redshift + velocity half power beam width of 50 km/s.1
CHAPTER 5: THE NEUTRAL HYDROGEN OF EDGE-ON SPIRAL GALAXIES

5.2.2 Archival observations

Four out of the six remaining galaxies in the Ch. 4 sample (ESO 240-G11, ESO 435-G25, ESO 437-G62 and ESO 487-G02) had been observed at 21-cm by Bureau, Freeman & Bosma with the ATCA (project no. C529). These data were retrieved from the ATCA archive and will be investigated here. The archival ATCA observations were carried out in 6A, 6B and 1.5D array configurations and used 512 channels covering a 8 MHz bandwidth (3.2 km s\(^{-1}\) channel\(^{-1}\)). These observations used the same calibration method as our ATCA observations (Sect. 5.2.1). Details of the observations can be found in Table 5.1. Note that at 21-cm the primary beam sizes of the ATCA and WSRT are 33\('\) and 36\('\) at full width half maximum (FWHM), respectively. Hence, all targeted galaxies are well within the primary beam.

The two remaining galaxies, ESO 288-G25 and NGC 891, are not included here. The H\,I distribution of the galaxy NGC 891 has been analyzed in detail in previous studies (Sancisi & Allen 1979; Rupen 1991; Swaters et al. 1997). The H\,I rotation curve of NGC 891 will be reanalyzed in Ch. 6, using the H\,I data of Swaters et al. (1997). For ESO 288-G25 H\,I synthesis observations are still lacking. Fortunately, the H\(\alpha\) major axis position-velocity diagram is well defined allowing an adequate determination of the rotation curve (Ch. 6).

5.2.3 The data reduction

The reduction of the visibility data was performed with the MIRIAD package. Using standard techniques, the visibilities were examined, interactively flagged for interference, and calibrated. A preliminary low spatial resolution data cube was then produced to locate the 21-cm line signal. The continuum signal was determined in the visibility domain by fitting a low order polynomial to the line free channels, and subtracted. Spectral line data cubes and continuum maps were then created at three different spatial resolutions. A full resolution version was produced using robust weighting of the visibility data without further tapering (using robust values of 0.5 for the ATCA observations and 0.1 for the WSRT observations). Two lower resolution versions were obtained by applying a Gaussian taper to the visibility data with FWHM corresponding to 30\('\) and 60\('\) in the image domain. For the archival ATCA data, which included the 6km array configuration, the low resolution line cubes were created by applying a Gaussian taper with FWHM corresponding to 10\('\) and 30\('\). Pixel sizes were chosen to be close to one third of the synthesized beam width and the field was imaged out to the primary beam half power points. The velocity axis of the H\,I data cubes is heliocentric and uses the radio definition, yielding a constant velocity increment between channels. As a compromise between sensitivity and velocity resolution the ATCA data were averaged in velocity to yield 256 independent channels and a channel spacing of 6.6 km s\(^{-1}\). The WSRT data of NGC 5529 were Hanning smoothed to suppress Gibbs ringing, yielding a velocity resolution of 33 km s\(^{-1}\) (FWHM).

Unfortunately, at this point it became clear that for 3 galaxies the sensitivity was insufficient to determine their H\,I properties: ESO 437-G62 remained undetected, whereas ESO 487-G02 and ESO 509-G19 were detected only after excessive velocity smoothing. The data for these galaxies were not further processed.

The spectral line data cubes and continuum maps for the fifteen detected galaxies were further processed and analyzed within the GIPSY environment. First, the CLEAN algorithm (Högbom 1974) was applied to correct for the effects introduced by limited visibility sampling. In each channel map, the region of H\,I emission to be cleaned was defined by a masked
version of the 60′ data cube. Following standard practice, this masked cube was created by retaining the H I emission in the channel maps above a level of twice the r.m.s. noise (2σ), and manually removing remaining noise peaks and grating rings. For the archival ATCA data the 30′′ data cube was used to create these clean masks. Then, at each resolution, the areas defined by the masks were cleaned down to 0.5σ. The clean components were finally restored using a Gaussian beam with a FWHM similar to that of the central peak of the dirty beam. The continuum maps were cleaned using the same approach.

5.3 Analysis

5.3.1 Radio continuum emission

21-cm continuum emission was detected in only five galaxies. Table 5.2 gives the continuum flux in the cleaned radio continuum maps at full resolution. The continuum fluxes are in agreement with those found for galaxies of similar Hubble type (Hummel 1981). For ESO 435-G50 there is a very bright continuum source projected onto the receding side of the optical disk which may perhaps be associated with this galaxy (S1.42 GHz = 109 mJy, not listed in Table 5.2. Interestingly, this bright source is double-lobed with the lobes apparently sticking out of the galaxy plane up to a projected height of ~30′′ (15 stellar disk scaleheights).

5.3.2 The neutral hydrogen emission

Global properties

The global profiles were constructed from the H I fluxes in the full resolution channel maps. In each of these channel maps the flux was calculated from the emission in the region of the clean masks and corrected for primary beam attenuation. The flux error was estimated by projecting the clean mask at eight different line-free locations, and integrating over each area separately. The standard deviation in the line-free ‘fluxes’ of these regions was then adopted as the flux error. For the four spirals for which companion satellites were also detected (see Sect. 5.3.4) only the emission from the main galaxy was included in the global profile. The resulting global H I profiles are presented in Fig. 5.3. The integrated primary beam corrected flux densities are listed in Table 5.3. The corresponding H I masses were calculated using the standard formula: \( M_{H I} = 2.36 \times 10^5 D^2 \int S \, dv \) where \( D \) is the distance of the galaxy in

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>( S_{1.42\text{GHz}} ) (mJy)</th>
<th>( \log_{10} P_{1.42\text{GHz}} ) (W Hz(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESO 263-G15</td>
<td>17.0 ± 1.4</td>
<td>21.28 ± 0.04</td>
</tr>
<tr>
<td>ESO 435-G25</td>
<td>4.5 ± 0.8</td>
<td>20.70 ± 0.08</td>
</tr>
<tr>
<td>ESO 564-G27</td>
<td>3.7 ± 1.3</td>
<td>20.51 ± 0.16</td>
</tr>
<tr>
<td>NGC 5170</td>
<td>14.1 ± 2.6</td>
<td>20.81 ± 0.08</td>
</tr>
<tr>
<td>NGC 5529</td>
<td>22.4 ± 0.9</td>
<td>21.66 ± 0.02</td>
</tr>
</tbody>
</table>

Notes – Columns: (1) Name; (2)&(3) Continuum flux and error; (4)&(5) Logarithm of the total power and error.
Mpc and $\int S \, dv$ is the flux density in Jy km s$^{-1}$. The basic assumption of this formula is that the H$\text{I}$ is optically thin. This assumption clearly holds with respect to the continuum absorption, since for each galaxy the continuum flux is small compared to the line flux in a single channel. The effect of H$\text{I}$ self-absorption is also small, according to a conservative estimates of the optical depth (Sect. 6.3.2). The errors listed for the flux density and H$\text{I}$ mass are the probable errors, calculated from the errors on the fluxes in the individual channels. The difference between the measured flux densities and those listed in LEDA (from single dish measurements) is shown in Fig. 5.1a. The agreement is excellent, except for ESO 240-G11 and ESO 435-G25. For those the radio synthesis measurements yield lower flux densities. This missing flux is not surprising given that the angular sizes of ESO 240-G11 and ESO 435-G25 are significantly larger than the angular size corresponding to the shortest spacing used in the observations ($\sim 6'$). Note that considering the uncertainties the flux densities agree remarkably well for the remaining galaxies: the uncertainties in the LEDA fluxes are probably overestimated.

The H$\text{I}$ global profiles were also used to calculate the systemic velocity and the line widths at the 20% and 50% levels. When double horned, the peak fluxes on the approaching and receding sides were used separately to determine these levels. Otherwise, the overall peak flux was used on both sides (which only applies to ESO 157-G18). The systemic velocity, listed in Table 5.3, was taken to be the average of the midpoints between the extreme velocities determined at 20% and 50% of the peaks. The derived systemic velocities agree well with the LEDA values (Fig. 5.1b), although, as for the flux densities, the uncertainties quoted in LEDA have been overestimated. The observed line widths were corrected for instrumental broadening and random motions according to the formalism of Verheijen & Sancisi (2001). Their instrumental correction is as follows:

### Table 5.3: H$\text{I}$ global properties

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$\int S , dv$ ±</th>
<th>$M_{\text{H}\text{I}}$ ±</th>
<th>$v_{\text{sys}}$ ±</th>
<th>$W_{R,20}$ ±</th>
<th>$W_{R,50}$ ±</th>
<th>$R_{\text{rec}}$</th>
<th>$R_{\text{app}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
</tr>
<tr>
<td>ESO 142-G24</td>
<td>22.9 ± 0.3</td>
<td>2.9 ± 0.1</td>
<td>1925.4 ± 0.7</td>
<td>242.0 ± 1.7</td>
<td>243.5 ± 2.4</td>
<td>2.4 ± 1.4</td>
<td>145 ± 147</td>
</tr>
<tr>
<td>ESO 157-G18</td>
<td>16.3 ± 0.3</td>
<td>0.8 ± 0.1</td>
<td>1378.8 ± 0.6</td>
<td>185.7 ± 1.7</td>
<td>187.5 ± 0.5</td>
<td>126 ± 0.7</td>
<td>107 ± 147</td>
</tr>
<tr>
<td>ESO 201-G22</td>
<td>14.2 ± 0.2</td>
<td>8.7 ± 0.1</td>
<td>4067.8 ± 0.4</td>
<td>334.1 ± 1.1</td>
<td>339.5 ± 1.2</td>
<td>127 ± 0.7</td>
<td>103 ± 147</td>
</tr>
<tr>
<td>ESO 240-G11</td>
<td>49.7 ± 0.5</td>
<td>14.7 ± 0.2</td>
<td>2842.9 ± 0.9</td>
<td>546.2 ± 2.3</td>
<td>542.7 ± 2.9</td>
<td>203 ± 0.7</td>
<td>225 ± 147</td>
</tr>
<tr>
<td>ESO 263-G15</td>
<td>19.5 ± 0.4</td>
<td>4.3 ± 0.1</td>
<td>2527.2 ± 1.2</td>
<td>334.3 ± 3.2</td>
<td>339.2 ± 3.6</td>
<td>145 ± 0.7</td>
<td>133 ± 147</td>
</tr>
<tr>
<td>ESO 269-G15</td>
<td>8.6 ± 0.2</td>
<td>3.7 ± 0.1</td>
<td>3386.1 ± 2.8</td>
<td>330.0 ± 8.0</td>
<td>326.4 ± 7.9</td>
<td>85 ± 0.7</td>
<td>88 ± 147</td>
</tr>
<tr>
<td>ESO 321-G10</td>
<td>3.9 ± 0.2</td>
<td>1.4 ± 0.1</td>
<td>3134.6 ± 1.8</td>
<td>303.4 ± 5.0</td>
<td>311.9 ± 5.0</td>
<td>66 ± 0.7</td>
<td>73 ± 147</td>
</tr>
<tr>
<td>ESO 416-G25</td>
<td>9.7 ± 0.2</td>
<td>9.5 ± 0.2</td>
<td>4988.6 ± 1.4</td>
<td>446.8 ± 4.0</td>
<td>447.6 ± 4.0</td>
<td>92 ± 0.7</td>
<td>113 ± 147</td>
</tr>
<tr>
<td>ESO 435-G14</td>
<td>16.0 ± 0.4</td>
<td>4.1 ± 0.1</td>
<td>2663.7 ± 1.6</td>
<td>269.8 ± 5.1</td>
<td>276.2 ± 3.9</td>
<td>93 ± 0.7</td>
<td>111 ± 147</td>
</tr>
<tr>
<td>ESO 435-G25</td>
<td>44.1 ± 0.3</td>
<td>9.7 ± 0.2</td>
<td>2474.7 ± 0.9</td>
<td>473.2 ± 2.2</td>
<td>471.4 ± 3.1</td>
<td>195 ± 0.7</td>
<td>230 ± 147</td>
</tr>
<tr>
<td>ESO 435-G50</td>
<td>7.3 ± 0.3</td>
<td>2.0 ± 0.1</td>
<td>2713.0 ± 1.0</td>
<td>173.9 ± 3.1</td>
<td>182.6 ± 2.7</td>
<td>73 ± 0.7</td>
<td>77 ± 147</td>
</tr>
<tr>
<td>ESO 446-G18</td>
<td>8.2 ± 0.3</td>
<td>7.4 ± 0.3</td>
<td>4771.6 ± 1.4</td>
<td>412.1 ± 4.0</td>
<td>421.1 ± 4.0</td>
<td>99 ± 0.7</td>
<td>100 ± 147</td>
</tr>
<tr>
<td>ESO 564-G27</td>
<td>39.7 ± 0.4</td>
<td>6.8 ± 0.1</td>
<td>2177.3 ± 0.5</td>
<td>323.3 ± 1.2</td>
<td>325.4 ± 1.6</td>
<td>189 ± 0.7</td>
<td>201 ± 147</td>
</tr>
<tr>
<td>NGC 5170</td>
<td>91.1 ± 0.6</td>
<td>8.2 ± 0.1</td>
<td>1500.7 ± 0.4</td>
<td>504.2 ± 1.1</td>
<td>508.6 ± 1.3</td>
<td>302 ± 0.7</td>
<td>314 ± 147</td>
</tr>
<tr>
<td>NGC 5529</td>
<td>43.2 ± 0.3</td>
<td>17.4 ± 0.1</td>
<td>2875.3 ± 0.4</td>
<td>574.8 ± 1.2</td>
<td>567.8 ± 1.3</td>
<td>188 ± 0.7</td>
<td>213 ± 147</td>
</tr>
</tbody>
</table>

Notes – The quoted velocities and line widths use the optical velocity definition. Columns: (1) Name; (2)&(3) Flux density and error; (4)&(5) H$\text{I}$ mass and error; (6)&(7) Systemic velocity and error; (8)&(9) Line width at the 20% level and error; (10)&(11) Line width at the 50% level and error; (12) H$\text{I}$ radius at the receding side; (13) H$\text{I}$ radius at the approaching side.
Figure 5.1: A comparison with the literature for (a) the flux densities, (b) systemic velocities and (c) line widths at the 20% level (see text).

\[
W_{20} = W_{20, \text{obs}} - 35.8 \left[ \sqrt{1 + \left( \frac{R}{23.5} \right)^2} - 1 \right], \\
W_{50} = W_{50, \text{obs}} - 23.5 \left[ \sqrt{1 + \left( \frac{R}{23.5} \right)^2} - 1 \right] \tag{5.1}
\]

where \( R \) is the velocity resolution (FWHM). This correction is based on approximating the edges of the global profile, which are mostly due to turbulent motion, with a Gaussian of dispersion of 10 km s\(^{-1}\). The corrections typically amount to a 20–25 km s\(^{-1}\) reduction in width. To enable a meaningful comparison of the corrected widths with the literature, the raw literature values were gathered (Table 5A.1) and corrected for instrumental broadening in the exact same way. The derived widths at the 20% level are compared to these literature values in Fig. 5.1c. The line widths are in agreement; the weighted mean of the difference \( W_{20} - W_{20, \text{lit}} \) is \(-0.4 \pm 1.6\) km s\(^{-1}\), whereas the r.m.s. scatter is 14 km s\(^{-1}\). For the line widths at 50% level the agreement is comparable (not shown).

The correction for random motion is based on the empirical formula of Tully & Fouque (1985):

\[
W_{R,l}^2 = W_l^2 + W_{t,l}^2 \left[ 1 - 2 \left( \frac{W_l}{W_{c,l}} \right)^2 \right] - 2 W_l W_{t,l} \left[ 1 - e^{-\left( \frac{W_l}{W_{c,l}} \right)^2} \right] \tag{5.2}
\]

where the subscript \( l \) refers to the level at which the line width was determined, \( W_{c,l} \) is the line width which defines the transition between quadrature summation (at small line widths) and a linear correction (at larger line widths), and \( W_{t,l} \) is a constant representing the HI random motions. We adopt \( W_{c,20} = 120 \) km s\(^{-1}\), \( W_{c,50} = 100 \) km s\(^{-1}\) and \( W_{t,20} = 22 \) km s\(^{-1}\), \( W_{t,50} = 5 \) km s\(^{-1}\) in order to probe the maximum rotation (Verheijen & Sancisi 2001). The corrected line widths are listed in Table 5.3.

The \( \text{HI} \) distribution

The \( \text{HI} \) column density maps were obtained by taking the zeroth moment of the masked channel maps (Fig. 5.3). Since the area containing \( \text{HI} \) emission is different in each channel, the noise in the column density map varies according to the number of channels summed at each position. To facilitate the interpretation of the \( \text{HI} \) column density maps, this noise map
was calculated according to \( \sigma_{\text{total}} = (n_{\text{chan}})^{1/2} \sigma \), where \( n_{\text{chan}} \) is the number of summed channels and \( \sigma \) is the actual r.m.s. noise level in a single channel map (the correlated noise introduced by the continuum subtraction is negligible). For NGC 5529 the data were Hanning smoothed. In this case we used \( \sigma_{\text{total}} = (n_{\text{chan}} - \frac{3}{4})^{1/2} \frac{4}{\sqrt{6}} \sigma \) (Verheijen & Sancisi 2001). From the column density map and this noise map a signal-to-noise map was constructed. Then, the average flux density of the pixels in the column density map with a signal-to-noise ratio between \( 2 \frac{3}{4} \) and \( 3 \frac{1}{4} \) was calculated. This signal-to-noise level is indicated in Fig. 5.3 by a thick contour.

The l.o.s. projection of an edge-on H\textsc{i} layer entails that each observed position contains information on a large range of galactocentric radii. The face-on H\textsc{i} surface density profile can be retrieved by de-projecting the observed radial H\textsc{i} distribution under the usual assumptions that the H\textsc{i} distribution optically thin and axisymmetric. Any large deviations from axisymmetry can then be investigated by comparing the results from the approaching and the receding sides. The observed radial H\textsc{i} distribution was de-projected following the method outlined in Warmels (1988). First, the so-called strip integral was calculated by integrating the H\textsc{i} column density map perpendicularly to the major axis, as defined by the dynamical center and position angle of the stellar disk (Table 4.4). The approaching and the receding sides of this strip integral are de-projected separately, using Lucy’s (1974) iterative deconvolution method. The iteration process is halted at the point at which it produces a reduction in \( \chi^2 \) less than 10% (typically at 10–15 iterations). The inferred face-on H\textsc{i} surface density profiles are plotted in Fig. 5.3. The radii at which the azimuthally-averaged H\textsc{i} surface density drops below 1 M_\odot pc\(^{-2}\) were determined for the approaching and the receding side separately. These H\textsc{i} radii are listed in Table 5.3.

Note that Warmels’ (1988) method has two disadvantages. First, it overestimates the H\textsc{i} surface density in the central parts (at radii smaller than 1–2 beam FWHM, Warmels 1988; Swaters 1999). For a poorly resolved edge-on spiral this may lead to an over-interpretation of the major axis position-velocity diagram: rotational velocities could be assigned at small radii even when in reality no H\textsc{i} is present. Secondly, although comparing the receding and approaching sides gives a rough estimate, the method does not provide error estimates. In Ch. 6, an alternative method will be introduced which attempts to lift these drawbacks by determining both the H\textsc{i} surface density profile and the rotation curve from the position-velocity diagram.

Finally, the H\textsc{i} column density map was also used to determine the projected H\textsc{i} layer thickness as a function of projected radius. For this, Gaussians were fitted to profiles extracted from a H\textsc{i} column density map which was constructed from a version of the channel maps smoothed to a circular beam. These profiles were extracted perpendicularly to the major axis at an interval corresponding to two-thirds of the circular beam FWHM. The fitted Gaussian centroids and 1\( \sigma \) dispersions are shown in Fig. 5.3.

**The H\textsc{i} kinematics**

The H\textsc{i} kinematics were studied using the major axis position-velocity (XV) diagrams (see Fig. 5.3). These XV diagrams were extracted from the full resolution data cubes by integrating the H\textsc{i} emission perpendicularly to the major axis as defined by the stellar disk center and position angle (Table 4.4). For NGC 5529, which has two nearby satellites connected to the main galaxy via H\textsc{i} bridges (Sect. 5.3.3), the anomalous H\textsc{i} was excluded while forming the XV diagram.
In first instance, the H I rotation curves were derived from these XV diagrams using the envelope-tracing technique, also often referred to as the terminal-velocity or edge-fitting method (Sancisi & Allen 1979; Olling 1996; Sofue 1996; García-Ruiz et al. 2002). The basic assumptions of this method are that the H I is (1) in perfect circular rotation and (2) detected everywhere along the line-of-nodes. Under these assumptions the extreme-velocity envelope of the major axis XV diagram traces the H I along the line of nodes (see Fig. 6.1 for a sketch of the geometry). Provided that a proper correction is made for instrumental broadening and turbulent motion this envelope can thus be used to derive the rotation curve. This correction, in essence a deconvolution, is what differs between the various implementations of the envelope-tracing method in the literature.

Here, a series of Gaussian least-squares fits was made to the extreme-velocity side of each velocity profile along the major axis (see García-Ruiz et al. 2002, for an illustration). In these fits the Gaussian dispersion was fixed at $\sigma_G = (\sigma_{H I}^2 + \sigma_{instr}^2)^{1/2}$, where $\sigma_{H I}$ is the H I velocity dispersion and $\sigma_{instr}$ is the velocity resolution. According to H I observations of face-on galaxies the turbulent motion of the H I is characterized by a vertical velocity dispersion of about 8–13 km s$^{-1}$ within the region of the stellar disk and 6–8 km s$^{-1}$ at larger radii, (van der Kruit & Shostak 1982; Dickey, Hanson, & Helou 1990; Kamphuis 1993). For our present purpose we are mainly interested in the region corresponding to the stellar disk and, assuming that the H I velocity dispersion is isotropic, we adopt a constant value $\sigma_{H I} = 10$ km s$^{-1}$. In each Gaussian fit in the series, the upper fitting boundary was fixed at the highest velocity showing emission above three times the r.m.s. noise level. In the first fit, three channels towards lower velocities were included, in the second four channels, etc., until the channel corresponding to the peak emission was reached (cf. García-Ruiz et al. 2002). The fit with the smallest reduced $\chi^2$ was retained as the best fit, with the peak velocity of the fitted Gaussian defining the rotation. The errors are estimated according to the formula of García-Ruiz et al. (2002) derived from Monte Carlo simulations: $\sigma_{v_c} = 4 \sigma_G / \sqrt{n_{ps} \cdot (S/N)}$, where $n_{ps}$ is the number of channels per $\sigma_G$ and $S/N$ is the ratio of the amplitude of the fitted Gaussian to the r.m.s. noise level in a single channel.

The derived rotation curves are overlayed on the major axis XV diagrams in Fig. 5.3. While in general the least-squares fits to each of the major axis velocity profiles were well behaved, in first instance they did not converge for ESO 157-G18, ESO 435-G14 and ESO 446-G18. This was caused by the fact that the extreme-velocity side of the velocity profiles was steeper than that implied by an H I velocity dispersion $\sigma_{H I} = 10$ km s$^{-1}$. For these galaxies $\sigma_{H I}$ was lowered until the fits did converge, yielding values of 6 km s$^{-1}$ for ESO 157-G18 and ESO 446-G18, and 7 km s$^{-1}$ for ESO 435-G14. Since ESO 157-G18 and ESO 435-G14 are small spirals, this would suggest that the H I velocity dispersions are smaller in dwarfs. However, ESO 446-G18 is clearly a massive spiral, and for the other two small systems in the sample (ESO 142-G24 and ESO 435-G50) the fits using $\sigma_{H I} = 10$ km s$^{-1}$ were well behaved.

Notes on the envelope-tracing method

Application of the envelope-tracing method to artificial data of axisymmetric H I layers in perfect circular rotation indicates that it works reasonably well at large projected radii (García-Ruiz et al. 2002). The reason is that at those radii the rotation curve is approximately flat, such that the extreme-velocity envelope of the XV diagram is only mildly contaminated by beam smearing (i.e. the presence in a single velocity profile of emission from neighboring
Figure 5.2: The envelope-tracing method applied to a simulated edge-on XV diagram of NGC 2403 (see Fig. 6.1 for the XV diagram), illustrating that the inferred rotation curve differs from the true curve and depends on the data quality. (a) – Comparison of the velocities found by tracing the envelope (symbols) with the true rotation curve (solid line). Squares/circles show the results of the Gaussian fits that include emission down to a level of 0.5/0.1 times the peak emission. The bar indicates the beam size. (b) – The envelope fits (dashed and dotted Gaussians) for a single velocity profile at a projected radius of 7 kpc (solid line). The vertical lines show the level down to which emission was included in the fits, and the arrows indicate the inferred peak velocities.

positions due to the finite spatial resolution) and l.o.s. projection. There is however a small systematic error introduced by the fact that the envelope is not solely due to the H I at the line of nodes, as assumed. Instead, the envelope also contains emission from the high velocity tails of H I clouds located in front of and behind the line of nodes (but seen in projection). This H I causes the high velocity side of the observed line profiles to deviate from an exact Gaussian tail with dispersion $\sigma_{\text{H I}}$ (cf. Olling 1996). The strength of this deviation mainly depends on the H I surface density distribution. As a consequence, the result of the envelope-tracing method depends on the part of the envelope included in the fit.

The effect is illustrated in Fig. 5.2 for a simulated edge-on view of the intermediately inclined spiral NGC 2403, based on the H I density profile and rotation curve obtained by Fraternali et al. (2002). See Sect. 6.2.1 for a contour representation of this artificial XV diagram and details on its construction. The use of upper fitting boundaries at relatively low velocities, as would be used in case of poor signal-to-noise data, yields rotation velocities that are systematically lower than the true rotation (squares). High upper fitting boundaries on the other hand clearly yield velocities which are systematically higher than the true rotation (circles). Although this error is relatively small at large radii, reaching values of $\sim 5$ km s$^{-1}$, it is systematic. More importantly, at small projected radii the discrepancy can become much larger (Fig. 5.2). This additional effect is caused by beam smearing, which is contaminating the extreme-velocity side of the velocity profiles with emission from larger projected radii. The beam-smearing effect by itself leads to an over-estimate of the rotational velocities at small projected radii (see also García-Ruiz et al. 2002). For poorly resolved edge-on spirals, the steepness of the inner rise of the rotation curves may thus be overestimated. Note that this
Analyzing is contrary to the underestimation of the rotation curves of less-inclined spirals that occurs when beam smearing is not taken into account in deriving the velocity field (Begeman 1987). A possible solution to the fundamental problem of beam smearing in edge-on spirals is to fit Gaussians to the edges of the velocity envelope in the spatial direction as well, and adopt the minimum of both curves as the rotation curve (García-Ruiz et al. 2002). However, this approach does not take into account the fact that a large fraction of the emission at small projected radii is due to H\textsubscript{I} in the outer parts of the galaxy seen in projection. For example, the proposed method would assign rotational velocities at small radii even in case of a central H\textsubscript{I} hole. We therefore prefer a more cautious approach and simply excluded the envelope-tracing results in the inner parts. A more complete analysis of the rotation curves is deferred to Ch. 6. There the entire XV diagrams will be modeled using the rotation curves derived here as initial estimates. This approach implicitly corrects for the effects of the l.o.s. projection and beam smearing and provides a more robust error analysis.

**Data presentation**

The H\textsubscript{I} distribution and kinematics of each galaxy is presented in Fig. 5.3. From left to right, top to bottom these figures show:

- **Optical image** – The first panel shows an optical image rotated according to the center and position angle of the stellar disk (Table 4.4). The white cross marks the dynamical center. The position angle and the optical passband are indicated in the upper left and right, respectively.

- **Column density map** – The H\textsubscript{I} column density distribution at full resolution (corrected for primary beam attenuation) overlayed on the optical image. Contour levels are 1/9, 2/9, ... , 8/9 times the peak column density, unless the figure caption indicates otherwise. The thick contour corresponds to the signal-to-noise level of three. The dots indicate the loci of the peaks of the Gaussians fitted to the vertical H\textsubscript{I} distribution. The peak column density and the average column density at the signal-to-noise level of three are listed next to the plots.

- **Renzogram** – The so-called renzogram, overlayed on the optical image, shows for a number of full resolution channel maps a contour drawn at 4 times the r.m.s. noise level. A renzogram is a compact way of showing the H\textsubscript{I} distribution in the channel maps. The contour line styles and the corresponding helio-centric velocities (radio definition) for each of the selected channels are listed next to this panel.

- **XV diagram** – The integrated position-velocity diagram (radio definition). Contour levels are -4, -2, 2, 4, 6, 8, etc., in units of the r.m.s. noise in the XV diagram, unless indicated otherwise in the figure caption. The r.m.s. noise ($\sigma_{XV}$) is listed next to the plots. The dots show the rotation curve derived using the envelope-tracing method. The horizontal and vertical lines denote the dynamical center and the H\textsubscript{I} systemic velocity, respectively. The spatial and velocity resolutions (FWHM) are indicated by the cross in the lower left.

- **Global profile** – Primary beam corrected H\textsubscript{I} flux as a function of helio-centric velocity (radio definition).

- **Surface density profile** – Face-on H\textsubscript{I} surface density profile obtained using the method of Warmels (1988).

- **Projected thickness** – The dispersion obtained by fitting Gaussians to the (projected) vertical H\textsubscript{I} distribution as a function of projected radius, both before (dots) and after (circles) correction for the spatial resolution. The circular beam of the smoothed version of the H\textsubscript{I} column density map is indicated. This panel is omitted when the vertical distribution is unresolved.
Figure 5.3: The H\textsc{i} distribution and kinematics for the full sample. A detailed description is given in Sect. 5.3.2, p. 101.
Figure 5.3: (continued) Notes: ESO 269-G15 – The XV diagram has been Hamming smoothed.
The renogram was constructed using a level of 3. Both XY diagrams were Hanningsmoothed.

Figure 5.3: (continued) Notes: ESO 321-610 – The renogram was constructed using the Hanningsmoothed data cube and a level of 3. ESO 416-25 – The renogram was constructed using a level of 3.
Figure 5.3: (continued) Notes: ESO 435-G25—The HI column density map, renzogram, and X-Y diagram were taken from the 10 arcsec resolution datacube synthesized beam 14.5'' × 28.8''. Contour levels in the X-Y diagram are 4, 2, 2, 4, 8, 12, 16, 20, and 24 times X-Y.
Figure 5.3 (continued): Notes: ESO 435-G50 - The XY diagram has been Hannings-smoothed. The tensorgram was constructed using a level of 3P.
CHAPTER 5: The Neutral Hydrogen of Edge-on Spiral Galaxies

Figure 5.3: (continued) Notes: For ESO 564-G27 and NGC 5170, the contour levels in the XV diagram are 4, 2, 4, 8, 12, 16, 20 and 24 times $\sigma$.
Figure 5.3: (continued) Notes: NGC 5529 – Contour levels in the XV diagram are $-4, -2, 2, 4, 8, 16, 24, 32, 40, 48$ and 56 times $\sigma$. Contour levels in the $\text{H} \, \text{I}$ column density map are $1.9, 3.8, 7.6, 15.2, 30.4$ and $60.8 \times 10^{20} \text{ cm}^{-2}$.

5.3.3 Notes on individual galaxies

**ESO 142-G24** – The $\text{H} \, \text{I}$ radius is only slightly larger than the stellar disk, which has a truncation at radius $R_{\text{max}} = 130''$ (Ch. 3). The $\text{H} \, \text{I}$ appears to be warped on both sides, following a pattern similar to that of the stellar disk. The distinct $\text{H} \, \text{I}$ feature detected in the XV diagram at a projected radius of $140''$ and $2020 \text{ km s}^{-1}$ lies just outside our optical image. The tentative $\text{H} \, \text{I}$ extension in the column density map (approaching side) is an artifact of the continuum subtraction.

**ESO 157-G18** – This dwarf system is lopsided, both in terms of its $\text{H} \, \text{I}$ kinematics and density distribution. This is directly apparent from the global profile, which is single peaked, and the XV map, which reflects a slowly rising/flat rotation curve at the approaching/receding side. No $\text{H} \, \text{I}$ is detected at radii beyond the stellar disk. The lopsidedness may be related to the presence of the small companion APMBGC 157+052+052 (Sect. 5.3.4), or the proximity of the S0 liner NGC 1553 and/or the elliptical NGC 1549.

**ESO 201-G22** – Radially, the $\text{H} \, \text{I}$ is more extended at the receding side, causing an asymmetry in the global profile. At that side, the $\text{H} \, \text{I}$ extends well beyond the stellar disk (stellar truncation radius $R_{\text{max}} = 102''$, Ch. 3). On the approaching side $\text{H} \, \text{I}$ emission is detected at the $4\sigma$ level outside the stellar disk ($R \approx 130''$), having a velocity $20$–$30 \text{ km s}^{-1}$ lower than the $\text{H} \, \text{I}$ at smaller radii. The vertical $\text{H} \, \text{I}$ distribution is barely resolved.
ESO 240-G11 – Although the H I in this fairly massive spiral is not detected far beyond the stellar disk, it appears to show a mild thickening just beyond $R_{\text{max}}$ (210′). On the approaching side the thickening is accompanied by a warping of the H I. XV diagrams taken parallel to and away from the major axis show that the warp forms a linear structure in the XV diagram, as if confined to a ring. Interestingly, the H I warp can be identified with faint emission in the $I$-band image. Further in, the H I is dominated by a ring or spiral arm with a radius $\sim$ 120′. At the receding side, the XV diagram is dominated by a curved structure, perhaps a strong spiral arm. The projected outer edge of this structure, at $R \approx 90′$, coincides with a ‘knee’ in the $I$-band surface brightness distribution (cf. Fig. 2A.1).

ESO 263-G15 – The H I is more extended at the receding side, causing an asymmetry in the global profile. The XV diagram is regular and consistent with a flat rotation curve beyond 40′. The low level signal away from the galaxy plane is artificial.

ESO 269-G15 – The density profile is fairly symmetric. The XV diagram on the other hand is asymmetric, the most striking being that the highest H I densities on the approaching side do not correspond to extreme-velocity envelope. On this side the H I appears to be in solid-body rotation, while on the receding side the rotation curve seems to reach a flat part. No H I was detected beyond the stellar disk.

ESO 321-G10 – This small Sa is structurally lopsided in H I. The rotation curve is poorly resolved spatially. For the dynamical center the optical center was taken (Table 2A.1).

ESO 416-G25 – On the approaching side the H I is more extended, reaching well beyond the truncation radius ($R_{\text{max}} = 74′$). The peak face-on surface density on this side is almost twice as low as that on the receding side.

ESO 435-G14 – Although the global profile is rather symmetric, the face-on surface density profiles are very different at both sides. The H I clearly extends further than the optical disk ($R_{\text{max}} = 80′$).

ESO 435-G25 – The H I in this large Sc spiral, which has a peanut-shaped bulge, displays rich structure in its distribution and kinematics. First, the H I, like the stars, extends to larger projected radii on the approaching side. Secondly, there is a moderate warping of the H I on both sides. On the approaching side this warp is also observed in the optical. On that side the rotation curve is approximately flat until it shows a drop of about 20 km s$^{-1}$ coinciding roughly with the onset of the warp ($R \sim 200′$). On the receding side the warping appears to be smaller. On this side the XV diagram is dominated by a curved high density ridge. Inspection of the data cube at full resolution shows that this ridge is actually a superposition of multiple linear features (rings). The extreme-velocity envelope at the receding side is slowly rising from $R = 50′$ up to $R = 160′$ and shows a remarkable upturn in the outskirts, reaching velocities higher than on the approaching side. Finally, the data hint at a vertical extension in the central region. Deeper observations are needed to confirm this.

ESO 435-G50 – The column density map shows a strongly warped H I distribution. The stellar disk does not appear to follow this H I warp. The rotation curve rises up to the last measured point.

ESO 446-G18 – Most of the H I emission of this galaxy is located on the receding side. On the approaching side, the H I shows an upturn which in the optical image coincides with a structure that resembles a spiral arm. The peak in the face-on surface density profile from the receding side coincides roughly with the ‘knee’ present in the $I$-band surface brightness distribution (cf. Fig. 2A.1).

ESO 564-G27 – This Sc is rather symmetric, both in density and kinematics. The H I extends...
further than the stellar disk \((R_{\text{max}} = 148\arcsec)\). In addition, it is warped on both sides, with the warp apparently starting outside the stellar disk. The rotation curve shows a local maximum on the receding side, at a projected radius of about two disk scalelengths.

**NGC 5170** – The H\(\text{I}\) is structurally lopsided. At the present sensitivity the H\(\text{I}\) does not extend far beyond the stellar disk. Remarkable is a local maximum in the rotation curve on the receding side at \(R \sim 240\arcsec\). This maximum corresponds to the projected end of a curved structure, probably a spiral arm, which dominates the XV diagram on that side. On the approaching side an inner ring-like structure with \(R \sim 120\arcsec\) dominates.

**NGC 5529** – This spiral is probably barred (App. 6A). In addition, its H\(\text{I}\) layer is warped, and, like the stellar disk, strongly perturbed on the approaching side. Hence, it is likely that a substantial fraction of the H\(\text{I}\) follows non-circular orbits, at least in the inner parts \((R \lesssim 50\arcsec)\). In that region, the extreme-velocity envelope is not representative of the circular speed curve. On the approaching side, the envelope rises sharply and peaks at a velocity of about 290 km s\(^{-1}\) at \(R \sim 90\arcsec\). Further out, at \(R \sim 120\arcsec\) it shows a steep drop with a minimum of 245 km s\(^{-1}\), which is followed by a gradual increase. Two small companions are located south of and close to the perturbed H\(\text{I}\) layer at a velocity close to the systemic velocity of NGC 5529. Interestingly, these companions are connected to the main galaxy via low column density H\(\text{I}\) bridges (see also Sect. 5.3.4). On the receding side, the envelope is less steep but again shows a local minimum at \(R \sim 120\arcsec\). The H\(\text{I}\) on the receding side is also warped. It further shows a faint extension to larger projected radii with an H\(\text{I}\) mass of about \(3.1 \times 10^8 \, M_\odot\). This gas cannot be identified with an optical companion and may be part of the warped H\(\text{I}\) layer.

### 5.3.4 Companion galaxies

The H\(\text{I}\) data cubes were searched for the presence of companion galaxies. Table 5.1 gives for each of the data cubes an indication of the mass sensitivity. In four cases, ESO 157-G18, ESO 240-G11, ESO 435-G25 and NGC 5529, a total of seven companions are detected. Their main properties are listed in Table 5.4. Each of these is discussed in the following.

**ESO 157-G18** – APMBGC 157+052+052 is located at a projected distance of 110\(\arcsec\) or about 3 disk scalelengths. Its apparent magnitude in \(I\)-band was determined using the photometry of de Grijs (1998) to be \(m_I = 14.87 \, \text{mag}\). At the adopted distance of the main galaxy this translates to a luminosity \(L_I = 1.2 \times 10^8 \, L_\odot\) (using \(M_\odot,I = 4.11\)), or about 10% of the \(I\)-band luminosity of ESO 157-G18. An interesting feature is an offset of \(\sim 7\arcsec\) (one third of the FWHM of the synthesized beam) between the H\(\text{I}\) and the optical centers of this companion. It is conceivable that this offset has resulted from an ongoing interaction with ESO 157-G18.

**ESO 240-G11** – At a projected distance of about 17' or about 20 disk scalelengths we find the small Sb galaxy ESO 240-G13. It has an \(I\)-band magnitude \(m_I = 12.41\) (Mathewson & Ford 1996) corresponding to a luminosity \(L_I = 6.2 \times 10^9 \, L_\odot\) (using \(M_\odot,I = 4.14\)). Together with ESO 240-G11 and ESO 240-G10 (not detected), ESO 240-G13 forms an isolated triple system (Karachentseva & Karachentsev 2000). The second detection, APMBGC 240-032-114 is a small companion to ESO 240-G11 at a projected distance of 14' or 18 disk scalelengths. Its photographic magnitude \(B_I = 15.87 \pm 0.12\) (Loveday 1996) corresponds to \(L_B = 8.8 \times 10^8 \, L_\odot\) (using \(M_\odot,B = 5.48\)).

**ESO 435-G25** – The optical counterpart of companion A at a projected distance of 12' (12 disk scalelengths) has an irregular appearance on the Digital Sky Survey (DSS). Companion B, at 14' (14 disk scalelengths), has only one tenth of the H\(\text{I}\) mass of companion A and is
Table 5.4: Companion galaxies detected in $H\,I$

<table>
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<tr>
<th>Galaxy</th>
<th>Companion</th>
<th>R.A. ($^\text{h},^\text{m},^\text{s}$)</th>
<th>Dec. ($^\text{d},^\text{m},^\text{s}$)</th>
<th>Vel. range ($\text{km},\text{s}^{-1}$)</th>
<th>$M_{H,I}$ ($10^8,\text{M}_\odot$)</th>
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</thead>
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<td>ESO 157-G18</td>
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<td>04 18 07.7</td>
<td>−55 55 43</td>
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<td>ESO 240-G13</td>
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<td>−47 46 27</td>
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<td>APMBGC 240-032-114</td>
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<td>−47 41 00</td>
<td>2742–2897</td>
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<tr>
<td>ESO 435-G25</td>
<td>A*</td>
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<td>−29 31 12</td>
<td>2635–2715</td>
<td>13.0</td>
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<tr>
<td></td>
<td>B*</td>
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<td>+36 12 08</td>
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<td>B*</td>
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<td>+36 12 02</td>
<td>2928–2990</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Notes – Columns: (1) Main galaxy; (2) Companion, an asterisk indicates the companion is listed neither in LEDA nor in the NASA/IPAC Extragalactic Database; (3)&(4) Companion central position; (5) Companion velocity range (helio-centric, optical definition); (6) Companion $H\,I$ mass (using the adopted distance of the main galaxy).

barely visible on the DSS. Given their small velocity differences with the systemic velocity of ESO 435-G25, both companions are probably satellites (both are outside the optical images of de Grijs 1998).

NGC 5529 – MCG +06-31-085a is located at a projected distance of $3.5\arcmin$ ($2.5\arcmin$ from the galaxy plane) and is connected to NGC 5529 via an $H\,I$ bridge. The $H\,I$ associated with this bridge amounts to about $6.5\,10^8\,\text{M}_\odot$. Companion B is found at a projected distance of about $30\arcsec$ from the plane of NGC 5529 and also appears to be connected to NGC 5529 via a bridge.

5.4 Discussion

Although the main purpose of the present $H\,I$ observations is to determine the $H\,I$ rotation curves (Ch. 6), the global $H\,I$ properties also provide valuable information.

5.4.1 The $H\,I$ mass-luminosity relation

It has been well established that spirals of higher optical (or near-infrared) luminosity tend to have a larger $H\,I$ mass (Roberts & Haynes 1994; de Blok et al. 1996; Broeils & Rhee 1997). This is illustrated in Fig. 5.4a for our sample of edge-on spirals, where we plot the $H\,I$ mass versus the $I$-band absolute magnitude. For the ESO-LV galaxies this magnitude was taken from de Grijs (1998, corrected for Galactic extinction, see Table 4.1), and for NGC 5170 from Mathewson & Ford (1996). For the $H\,I$ masses of ESO 240-G11 and ESO 435-G25 the single dish values were used due to missing flux at small spacings in the synthesis observations (Sect. 5.3.2). For comparison, the Ursa Major cluster sample of Verheijen & Sancisi (2001) is shown (crosses), using the $I$-band magnitudes from Tully et al. (1996) and adopting the HST Key Project distance of 20.7 Mpc (Sakai et al. 2000). A small offset between the two samples appears to be present, although the statistics are poor. Such an offset is expected on the basis of a larger amount of internal extinction due to the high inclinations of our sample galaxies (although several of the Ursa Major cluster spirals are also highly inclined). A rough estimate of the extinction effect can be obtained by comparing the average $I – K$ colors of
both samples. The average values for our sample and the Ursa Major sample are $2.3 \pm 0.4$ (1σ) (de Grijs 1998) and $1.7 \pm 0.4$ (1σ) magnitudes, respectively. This indicates that the effect of dust extinction is to lower the $I$-band luminosities by at least 0.6 $I$-band magnitudes (this lower limit is indicated by the arrow in Fig. 5.4a).

5.4.2 H$\text{I}$ richness

The H$\text{I}$ mass fraction or gas richness, $M_{\text{H}I}/L_I$, has been shown to decrease with increasing luminosity (e.g. Roberts & Haynes 1994; Verheijen & Sancisi 2001): spirals of higher luminosity tend to be less rich in H$\text{I}$. Fig. 5.4b shows this relation for our sample, again using the $I$-band luminosity. The relation appears to lie slightly above the one found for the Ursa Major cluster (Verheijen & Sancisi 2001). Unlike the small offset in the H$\text{I}$ mass luminosity relation, dust extinction is unable to explain this offset. Instead the offset probably indicates that our field spirals tend to be somewhat richer in H$\text{I}$ than the spirals of the Ursa Major cluster. The sample average is $M_{\text{H}I}/L_I = 0.7 \pm 0.5$ (1σ scatter) $M_\odot/L_\odot$. The H$\text{I}$ mass fraction shows no correlation with the stellar disk scalelength or stellar disk flattening.

5.4.3 The H$\text{I}$ mass-size relation

The H$\text{I}$ mass–luminosity relation (Sect. 5.4.1) is mostly one of size. Previous studies pointed out that the H$\text{I}$ mass correlates strongly with both the H$\text{I}$ diameter $D_{\text{H}I}$ (the diameter at which the H$\text{I}$ surface density reaches 1.0 $M_\odot$ pc$^{-2}$) and the optical diameter $D_{25}$ (measured from the 25.0 B-mag arcsec$^{-2}$ isophote). The relation between H$\text{I}$ mass and H$\text{I}$ diameter for our sample is shown in Fig. 5.5a (solid dots). It has a logarithmic slope of 1.95 and is within 0.1 dex of the relations found for samples of less-inclined spirals (e.g. Broeils 1992; Swaters 1999; Verheijen & Sancisi 2001). This good agreement suggests that H$\text{I}$ self-absorption can-
Figure 5.5: (a) $\text{H} \text{I}$ mass versus the $\text{H} \text{I}$ diameter (dots) and the stellar disk truncation diameter (circles). The solid and dashed lines show the linear least-squares fits (also indicated in the lower right corner). (b) Luminosity-linewidth relation in the $I$-band for 14 edge-on spirals, not corrected for internal extinction (solid dots). The solid line indicates a least-squares bisector fit, and the dotted line indicates the extinction corrected $I$-band luminosity-linewidth relation according to the HST Key project (Sakai et al. 2000).

not have removed more than about 20 percent of the $\text{H} \text{I}$ flux. The relation between $\text{H} \text{I}$ mass and the optical diameter $D_{25}$ loses its meaning for highly inclined galaxies. The reason is that the l.o.s. projection causes a higher surface brightness than in the face-on view, depending on the disk flattening, the stellar disk truncation radius $R_{\text{max}}$ and the dust distribution. The truncation diameter presents a natural measure of the stellar disk size allowing a more useful comparison with the $\text{H} \text{I}$ mass. The relation between stellar truncation diameter and the $\text{H} \text{I}$ mass is shown in Fig. 5.5a (open circles), using $2 R_{\text{max}}$ for galaxies with a single sided truncation. The relation of $\text{H} \text{I}$ mass with the stellar truncation diameter is similar to the one with the $\text{H} \text{I}$ diameter. Or, saying it differently, for the galaxies with detected truncations the radius at which the $\text{H} \text{I}$ surface density drops to $1.0 \, \text{M}_\odot \, \text{pc}^{-2}$ is close to the truncation radius, with an average $R_{\text{H} \text{I}}/R_{\text{max}} = 1.1 \pm 0.2 \, (1\sigma)$. The ratio of $\text{H} \text{I}$ radius to stellar truncation radius is in agreement with the disk galaxy formation model studied by van den Bosch (2001) for which $R_{\text{H} \text{I}}/R_{\text{max}}$ is close to unity for spirals with $v_{\text{max}} \gtrsim 100 \, \text{km s}^{-1}$. This galaxy formation model is questionable, however, since it does not predict the observed decrease in $R_{\text{max}}/h_R$ for stellar disks of a lower face-on central surface brightness (Ch. 3).

5.4.4 The luminosity-linewidth relation

The offset between the $\text{H} \text{I}$ mass-luminosity relation for our sample of edge-on spirals and the same relation observed in less inclined spirals (Sect. 5.4.1) pointed out that edge-on spirals suffer considerably from dust extinction. A similar offset is expected to show up in the luminosity-linewidth or Tully-Fisher relation (Tully & Fisher 1977). The luminosity-linewidth relation using the $I$-band luminosities (de Grijs 1998) and the line widths at the 50% level is shown in Fig. 5.5b, re-scaled to $H_0 = 71 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ (Sakai et al. 2000).
The $I$-band luminosities are uncorrected for internal extinction. The outlier, ESO 263-G15, has a regular H I XV diagram and a well-determined line width. Instead its (edge-on) luminosity has probably been overestimated. Given that ESO 263-G15 has a pronounced dust lane (Fig. 2A.1), it is likely that this overestimate is caused by a serious distance error. A least-squares bisector fit to the entire sample yields a slope $\alpha = 3.05 \pm 0.17^*$ and an intercept $\log_{10}(L_{100}/L_\odot) = 9.27 \pm 0.03$ (solid line). The dotted line indicates the $I$-band luminosity-linewidth relation according to the HST Key Project, which has a slope $\alpha = 4.0$ and an intercept $\log_{10}(L_{100}/L_\odot) = 9.39$ (Sakai et al. 2000). This relation uses luminosities that were extinction corrected to the face-on orientation according to the Tully et al. (1998) scheme. The uncorrected $I$-band relation defined by our edge-on systems (solid line) lies systematically below the HST Key Project $I$-band relation. Although the sample size is small, the shallower slope of the edge-on relation appears to be robust (a $5\sigma$ difference with the HST Key Project slope). This implies that the additional extinction in the edge-on orientation steadily increases with line width, from values close to zero magnitudes at $W_{R,50}/2 < 80$ km s$^{-1}$ to values on the order of a magnitude or more for $W_{R,50}/2 > 200$ km s$^{-1}$.

5.5 Summary

We have presented H I synthesis observations of 15 edge-on spiral galaxies for which the stellar disk structure and kinematics were studied in Chapters 2 & 4. The main purpose of these observations is the derivation of the H I rotation curves. These will allow us to construct dynamical models of the stellar disks and constrain the intrinsic stellar disk kinematics and stellar disk mass (Ch. 7).

Here, we analyzed the global properties, distribution and kinematics of the H I. On the whole, the H I is distributed regularly, showing no strong warps or massive companions. This reflects our selection against spiral galaxies that are optically irregular or strongly warped. The exception is the barred spiral NGC 5529, which is strongly perturbed in both the optical and the H I and has two companions connected to the main galaxy via H I bridges. Several of the spirals are mildly lopsided, but strong lopsidedness, both kinematically and structurally, is present only in ESO 157-G18. For 10 spiral galaxies with a stellar disk truncation we find an average ratio of the H I to truncation radius of $R_{HI}/R_{max} = 1.1 \pm 0.2$ ($1\sigma$). A comparison of the luminosity-linewidth relation of edge-on spirals with the relation found in less-inclined spirals indicates that the internal extinction increases towards more massive spirals. We point out that the envelope-tracing method for deriving the rotation curves of edge-on spiral galaxies is reliable only in the outer, flat parts of the rotation curve. At small radii the effects of beam-smearing and the projection have to be taken into account.

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* $L/L_\odot = L_{100}/L_\odot \left[ (W_{R,50}/2)/(100 \text{ km s}^{-1}) \right]^{4.14}$, $M_{\odot,I} = 4.14$
from the Netherlands Foundation for Scientific Research (NWO). The data analysis was performed using MIRIAD, distributed by ATNF, and GIPSY, developed at the Kapteyn Institute. We have made use of the LEDA database.

5A Raw line widths

In Table 5A.1 we list the uncorrected line widths at the 20 and 50 percent levels, from both the present synthesis observations and the literature. The line widths use the optical velocity definition.
Figure 5.3: (continued) Notes: ESO 240-G11 – The H I column density map, renzogram and XV diagram were taken from the 30 arcsec resolution data cube. The synthesized beam is 32.6 × 38.4 arcsec. The XV diagram contour levels are 4, 2, 1, 0.8, 0.4, 0.2, and 0.1 times XV. The XV diagram contour levels are 4, 2, 1, 0.8, 0.4, 0.2, and 0.1 times XV.