Neutral Hydrogen and Optical Observations of Edge-on Galaxies: Analysis

Based on a paper by J. García-Ruiz, R. Sancisi & K. Kuijken
MNRAS, to be submitted.

In this chapter we describe the analysis of the HI and optical data presented in chapter 4. 20 out of the 26 galaxies of our sample are warped, confirming that warping of the HI disks is a very common phenomenon in disk galaxies. Indeed, we find that all galaxies that have an extended HI disk with respect to the optical are warped. The warping usually starts around the edge of the optical disk. The degree of warping varies considerably from galaxy to galaxy. Furthermore, many warps are asymmetric, as they show up in only one side of the disk or exhibit large differences in amplitude in the approaching and receding sides of the galaxy. These asymmetries are more pronounced in rich environments, which may indicate that tidal interactions are a source of warp asymmetry. A rich environment tends to produce larger warps as well. The presence of lopsidedness seems to be related to the presence of nearby companions.

5.1 Introduction

Warps are still a puzzle in galactic dynamics, although they have been with us for more than three decades. Most of our knowledge about the properties of warps comes from a study by Briggs (1990) of 12 galaxies that were known to have warps. He pointed out that warps start around $R_{25}$ - $R_{1}$ and that the line of nodes of the warp is straight inside $R_{25}$ but tends to form a leading spiral outside.

But many questions still remain open. Recent work by Reshetnikov & Combes (1998) on stellar warps has shown the influence of the environment on warps, in the sense that there are more optically warped galaxies in dense
environments than in low-density regions. The relation between the optical and HI warps is not clear yet, because most of the warps start around the optical edge of the galaxy and their study is challenging.

The aim of our survey is to investigate where the warps start with respect to the stellar disk, their shape and degree of symmetry and the influence of the environment on their frequency and amplitude. We will also study the difference between the morphological and/or kinematical properties of warped and non warped galaxies, which may provide clues to understand the formation mechanism(s) for warps.

### 5.2 Warp statistics and shapes

The first question to address is how common warps are. Table 4.6 already shows that the outer parts of the majority of galaxies exhibit some departure from flat disks. We detect warps in 20 of our galaxies, of which 7 show a warp only on one side (see Table 5.1). If we consider only warps larger than 2°, the number of warps decreases to 17, of which 7 are only on one side. Taking into account that we will probably miss most of the warps with a line of nodes close to the direction perpendicular to the line of sight from us to the galaxy, it means that the vast majority of galactic disks are warped.

Warps normally start at the edge of the optical disk or further away. This means that for the warp to be visible there must be gas outside the optical disk. We looked at the galaxies in our sample with no warp to see if any of them had extended HI disks, i.e. if there was any galaxy with an extended HI disk (with respect to the optical emission) and no warp. As a measure of the optical extent of the galaxy we used \( \text{R}_{\text{opt}} \) (see section 4.3.1), which is more representative than \( \text{R}_{25} \), particularly in edge-on galaxies. We found that all the galaxies in our sample that have HI disks more extended than the optical are warped. If we consider each side of the galaxy independently, there is
only one exception to this rule: one side of UGC 7125 is warped, while the other remains flat, and both sides have HI more extended than the optical.

One of the most striking characteristics of the warps observed here is their asymmetry. To begin with, a considerable percentage of the warped galaxies show a warp only on one side. This is not due to an absence of HI on the opposite side: in all cases the gas disk on the unwarped side does extend to beyond $R_{\text{warp}}$. Sometimes (as in UGC 7321, 8246, 8396) there are hints of the beginning of a warp in that side but the data do not allow a firm detection of it.

However, the clearest sign of asymmetry in warps comes from galaxies with both sides warped. Figure 5.1 shows the warp asymmetry ($\alpha_{\text{asym}}$) with respect to the mean warp angle. Only galaxies with warps detected on both sides of the disk are plotted. We inspected the total HI maps of all our galaxies looking for tidal features that would clearly indicate strong tidal interaction with a nearby companion. Such interaction might produce a highly asymmetric warp. These galaxies are plotted as filled circles in Figure 5.1, and indeed they appear to possess more asymmetric warps than the rest of the galaxies. But the remaining warped galaxies also have large asymmetries. There are only 2 systems with large warps and high symmetry: UGC 6964 and UGC 6126. The other galaxies lie more or less on a straight line where the ratio of the asymmetry to the mean warp is of about 0.7. A galaxy with this asymmetry and a mean warp of 10° would have warps in each side of 6.5° and 13.5°, which is quite asymmetric.

Most of the galaxies with both sides warped are antisymmetric (S shape warps). We only have two cases of U-type warps, and both these galaxies are
Figure 5.2 — Density - RC - warp plots. For each galaxy, the rotation curve along the major axis, the radial HI density profile and the curve of warp are plotted. We have measured these quantities independently for the two sides of the galaxies, and here we present them together in the same plot. The top panel shows the rotation velocities and radial density profiles for both sides of the galaxy. The left axis shows the units for the rotation velocities, while the right axis applies to the density profiles. The bottom panel shows the warp curves for both sides. Because most of the warps have an S-shape, the warp curve derived for the left side has been inverted, to highlight symmetries or asymmetries between the two sides of the galaxy. With this process, both warp curves of a galaxy with a perfect S-shape symmetry (thus, antisymmetry) would fall on top of each other. One side is plotted with crosses (rotation curve and warp curve) and dotted line (density), and the other side is plotted with circles (rotation curve and warp curve) and solid line (density). The rotation curve and warp curves in the figure are shown at 2 different resolutions: the full resolution (small symbols) for the inner parts and the 30" resolution (bigger symbols) in the outer parts. The arrows in the bottom panel indicate the warp radius for the two sides of the galaxy. Errorbars have not been plotted in the warp curves for sake of clarity, they are shown in the atlas (in chapter 4).

strongly interacting with nearby companions and are very disturbed.

The warp curves, together with the rotation curves and the radial density profiles have been plotted in Figure 5.2. These plots show the shapes and amplitudes of the warps, and allow a comparison between features in the radial density profiles, rotation curves and warp curves. It is quite clear from Figure 5.2 that there are several distinct warp shapes: some galaxies have monotonically increasing warps (rising linearly or even faster), while others have warps that at some point rise slowly, and in some cases head back to the plane defined by the inner regions, like the southern warp in the Milky Way. Note that the rotation curves in Figure 5.2 have been calculated along the major axis and not along the warp line. This is the reason why the rotation curves often stop before the HI density drops to zero, as in UGC 6964.
Figure 5.2— continued
Figure 5.2 — continued
Figure 5.2—continued
Figure 5.2—continued
Warps in disk galaxies

5.3 Galaxy lopsidedness

Lopsidedness may have some connection with warping. If, for instance, the lopsidedness of a galaxy is caused by merging, and such merging process is also causing the warping, we would expect more pronounced warps in lopsided galaxies, and small or no warps in axisymmetric galaxies.

The first indication that lopsidedness may be the result of accretion or interactions with nearby companions comes from the fact that the lopsidedness we measure seems to depend quite strongly on the environment. In Figure 5.3 we have plotted histograms for the galaxies according to their density lopsidedness index for each type of environment: poor, intermediate and rich (see §4.4.9). Clearly, galaxies with no nearby companions are quite symmetric in mass, galaxies with companions not closer than 50" are somewhat more lopsided, and finally, all galaxies with a lopsidedness greater than 5% have a companion closer than 50". The dependence of lopsidedness on environment found here is remarkable if one takes into account the uncertainty of the classification of the environment. The kinematical lopsidedness seems also to depend somewhat on the environment,
Chapter 5: HI & Optical Observations of edge-on galaxies: Analysis

Figure 5.4—Warp angles for each environment class (see definition in §4.4.9). The left panel shows the warps of galaxies in poor environments, the middle panel the galaxies in intermediate environments, and the right panel those in rich environments. For each galaxy, the larger of both side's warp angles has been plotted on the x axis, versus the smaller one on the y axis (so the upper left part of the plots is empty). The galaxies with a detected warp on only one side lie in the y=0 line, and the non warped galaxies are in the origin. The dotted line indicates equal warp angles on both sides of the galaxy.

as isolated galaxies have lower kinematical lopsidedness than the rest of the galaxies. The way both lopsidedness indices are measured actually makes them lower limits due to the fact that the galaxy is edge-on: to measure our lopsidedness indices we are comparing the approaching and receding sides of the galaxy (integrated along the line of sight), thus if the galaxy is asymmetric in the direction along the line of sight we would not be able to detect it. We did not find a clear correlation between kinematic and density lopsidedness in our galaxies.

5.4 Warps and environment

The lopsidedness seems to be correlated with the environment, in the sense that in rich environments galaxies are more lopsided. It has been claimed (Reshetnikov & Combes, 1998) that optical warps also depend on the environment, in the sense that galaxies in rich environments are more commonly warped than isolated galaxies. These authors concluded that this could indicate that tidal interactions are the cause of warps, or at least that they reinforce them. In a study of the influence of minor mergers on the warping of optical disks Schwarzkopf & Dettmar (2001) found warps in all their merging systems, but in only half of their control sample. The amplitude of the warps in the merging systems was larger as well. They concluded that tidal interaction does generate warps but that this mechanism does not account for all the observed ones.

We checked our sample to see if these relations hold for the larger HI warps as well. Table 5.1 shows that, if anything, the trend in frequency for the occurrence of HI warps in our sample seems to go in the opposite sense:
Table 5.2— Comparison of warps in the optical (Sánchez-Saavedra et al., 1990) and HI (this work). The first two columns show the NGC and UGC names, and the third and fourth columns show the sense of the detected warp, which can be either N (anti-clockwise), S (clockwise) or U (non antisymmetric warp). NGC 5229 doesn’t have a clear detected warp in HI.

<table>
<thead>
<tr>
<th>Galaxy (NGC)</th>
<th>Optical (UGC)</th>
<th>HI</th>
</tr>
</thead>
<tbody>
<tr>
<td>3432</td>
<td>5986</td>
<td>—  U</td>
</tr>
<tr>
<td>3510</td>
<td>6126</td>
<td>N  N</td>
</tr>
<tr>
<td>3600</td>
<td>6283</td>
<td>N  S</td>
</tr>
<tr>
<td>4010</td>
<td>6964</td>
<td>N  S</td>
</tr>
<tr>
<td>4144</td>
<td>7151</td>
<td>—  —</td>
</tr>
<tr>
<td>5023</td>
<td>8286</td>
<td>—  N</td>
</tr>
<tr>
<td>5229</td>
<td>8550</td>
<td>S  S?</td>
</tr>
<tr>
<td>5297</td>
<td>8709</td>
<td>—  —</td>
</tr>
<tr>
<td>5301</td>
<td>8711</td>
<td>N  N</td>
</tr>
</tbody>
</table>

Galaxies in poor environments are more frequently warped than galaxies in dense environments. However, all galaxies with an extended HI disk with respect to the optical disk are warped, therefore the frequency of warps depends on the extension of the HI disks. Thus, in our sample there are more galaxies with no extended HI in rich environments than in poor environments. The warp parameters (amplitude and asymmetry) are illustrated as a function of environment in Figure 5.4.

There seems to be a tendency for galaxies in poor environments to be more prone to warping, but to have smaller warp angles than in rich environments. Warps also seem to be more symmetric in poor than in rich environments. The explanation for the asymmetry and higher amplitude of the warps in rich environments could lie in the tidal interaction with neighboring galaxies (e.g. UGC 5452, UGC 8396). The indication that galaxies in poor environments are more frequently warped may mean that tidal interactions are not the only mechanism that produces warps.

5.5 HI vs. optical warps

As mentioned above, warps may show a different behavior with respect to environment when observed in the optical or in HI. Unfortunately, not much work has been done about the relationship between HI and optical warps in the same galaxies, and none with high quality HI and optical data.

Sánchez-Saavedra et al. (1990) studied optical warps using POSS plates. They looked at all NGC galaxies in the northern hemisphere that had $\log R_{25}$ larger than 0.57, and determined whether the warp was clockwise or anticlockwise (S or N warps). Nine of their galaxies are in our sample, so we
decided to compare with our results and find out whether the sense of the warp is the same or not. Table 5.2 shows the results. Four of the galaxies in common do not appear to be warped in the Sánchez-Saavedra et al. (1990) study. Two of the warped galaxies have the same sense as found in this work, two the opposite, and the last one has a dubious warp in HI. In the case of UGC 6964 the difference may be due to dust and/or spiral arms. The optical image shows patchy emission and it indeed looks bent with an 'N' shape, while the HI bends in the opposite direction in quite a spectacular way. In the other case, UGC 6283, the difference is probably due to the shape of the warp curve itself. The disk bends first slightly in one direction, turns back and then bends in the opposite direction. The warp seen in the optical is probably tracing that first small 'kink' of the warp shape. So in this case the warp is correctly detected, but the general sense of the warp is not, because the optical disk ends before the HI warp changes direction. This galaxy is not completely edge-on and it is possible that this 'kink' could be due to the presence of spiral arms.

Our conclusion from this comparison is that the stellar warps studied thus far are not directly comparable to the HI warps. The latter occur at larger galactocentric radius, and generally have a considerably higher amplitude. At this point it is unclear whether (faint) stellar disks extend to these radii or not.

5.6 The radial HI profile and warping

In our search for a common property among warped galaxies (with respect to the non warped ones), we have compared the radial HI profiles of both types of galaxies. We have excluded galaxies that are interacting with nearby neighbors, because a tidal interaction probably affects the radial profile of a galaxy. We also removed galaxies with very small warps. Thus we have constructed two groups of galaxies: the bona fide warped galaxies, containing UGC 1281, 2459, 3137, 3909, 5459, 6964, 7125, 7321, 7774, 8286 and 8711; and non-warped galaxies: UGC 7089, 7090, 7151, 7483, 9242.

We have scaled the radial profiles using $R_{HI}$ as unit radius and the radial densities with $M_{HI}/D^2$, where D is the distance to the galaxy. We have tried other scaling factors (such as the radius where the density drops to 0.5 the peak density; and the area below the profile) with no effect on the conclusions presented here.

Figure 5.5 shows the individual profiles as well as the mean profile for each group of galaxies. A histogram showing the radius at which warps begin is also plotted. These plots show that warped galaxies are more extended in HI than non warped galaxies: at around 1.1 $R_{HI}$ the HI density of a galaxy with no warp falls much faster than that of a warped galaxy, which still has some more gas extending up to 1.5 and even 2 $R_{HI}$. This extra gas we see
Figure 5.5— Radial HI density profiles. The plot on the left shows the HI profiles for bona fide warped (upper panel) and non-warped (lower panel) galaxies (see §5.6 for definition of both groups). The profiles of individual warped and non-warped galaxies are plotted in dotted line, and the thick line is the average profile for each group. In the lower panel a histogram of the radius where the warp begins is overplotted. We have treated both sides of the galaxy independently, to take into account that two of our bona fide warped galaxies have only one-sided warps. The plot on the right shows the mean profiles for both bona fide warped (solid line) and non warped galaxies (dotted line).

in the warped galaxies is the same feature as the “shoulder” mentioned in Sancisi (1983).

Thus, the typical radial HI profile of a warped galaxy has the following shape: in the inner parts it is roughly constant or slowly decreases, around 0.5 \( R_{\text{HI}} \) it drops faster, and further out it extends at low levels ending at 1.5-2 \( R_{\text{HI}} \). It is in the second part of the profile (the steepest part, around the optical edge) where a warp develops in most of the galaxies.

We have also measured the extent of the HI with respect to the optical in both non warped and warped galaxies. Figure 5.6 shows the histograms for both groups, and indicates that warped galaxies have HI layers more extended with respect to the optical than galaxies with no warps. There is no galaxy in our sample with an extended HI disk with respect to the optical disk but no warp.

### 5.7 Warp amplitudes

We have plotted the warp amplitude (warp angle) vs. the width of the global HI profile at 20% level and vs. the extent of the HI with respect to the optical in Figure 5.7. The objects with obvious interaction with nearby companions are shown with large filled symbols. For this class of objects there seems to
Chapter 5: HI & Optical Observations of edge-on galaxies: Analysis

Figure 5.6— Histograms of the ratio $R_{\text{HI}}$ to $R_{\text{opt}}$ for bona fide warped (left panel) and non-warped (right panel) galaxies (see §5.6 for definition of both groups). The histograms show that warped galaxies are more extended in HI than the non-warped ones.

be a relation between the width of the profile and the warp amplitude in the sense that galaxies with broader profiles have smaller warps.

For the rest of the galaxies we have not found any relation with either the visible mass of the galaxy or the width of the global HI profile. If warps are caused by some force realigning the disk of the galaxy (as opposed to inflow of HI gas at a different angle than that of the inner disk), this means that the force should scale (on average) with the mass of the system. The amplitude of warps does not seem to be related to either the density lopsidedness or the kinematical lopsidedness. The same is true for the asymmetry of warps.

Figure 5.7 also shows the amplitude of the warps vs. the HI extent with respect to the optical. We can see that non warped galaxies are at low $R_{\text{HI}}/R_{\text{opt}}$, and that large warps only occur in galaxies with large $R_{\text{HI}}/R_{\text{opt}}$.

5.8 Mean surface density

It has been shown that there is a tight relation between HI mass and HI radius (Broeils & Rhee, 1997; Verheijen, 1997), with a slope close to 2 in a log-log scale. Figure 5.8 shows both $M_{\text{HI}}/D^2$ vs. $D_{\text{HI}}/D$ relation (measured quantities) and $M_{\text{HI}}$ vs. $D_{\text{HI}}$ (after multiplication by the distance to each galaxy). The slope of the relation changes from 1.85 to 1.99 in these plots, which illustrates how uncertainty in the distances to the galaxies can artificially ‘enhance’ relations and alter the slopes. But even a slope of 1.85 implies that the average HI surface density ($\langle \sigma_{\text{HI}} \rangle$) is more or less constant from galaxy to galaxy. The average value is $4.0 \pm 1.0 M_\odot pc^{-2}$, consistent with the measure-
Warps in disk galaxies

Figure 5.7—Warp amplitude vs. the width of the global HI profile at 20% level (left) and vs. $R_{20}/R_{c,0}$ (right). The symbols indicate different environmental conditions: isolated (open circles), intermediate (squares), rich environment (empty stars) and interacting (filled large stars). For a detailed description of the environment classification, see §4.4.9

ments by Broeils & Rhee (1997).

If we assume that galaxies are formed with this constant mean surface density, what will happen if gas is accreted at a later time? If the accreted mass is much smaller than that of the host galaxy the result will probably be to decrease the mean surface density of the galaxy (the change in $D_{HI}$ dominates). If this picture is correct, a lower mean surface density would mean a richer history of accretion.

Figure 5.9 shows a plot of the asymmetry in the warps vs. the mean HI surface density. Galaxies with larger mean surface densities seem to possess more symmetric warps.

5.9 Conclusions

We have studied the warps in the outer HI layers of a sample of 26 edge-on galaxies using the data presented in chapter 4. We have also studied the density and kinematic lopsidedness of the HI disks. We have not been able to determine the source for the warping of the HI disks. However, we have provided data on warp amplitudes, asymmetry, occurrence rates and their relationship with the environment that is a step forward in our understanding of warps.

There are indications that environment may play a role on warping. In rich environments optical warps are larger and more frequent (Reshetnikov & Combes, 1998), and HI warps are larger and more asymmetric. However, the ubiquity of warps, even in low density regions and the symmetry
Chapter 5: HI & Optical Observations of edge-on galaxies: Analysis

Figure 5.8— HI mass vs. HI radius for all the galaxies in the sample. The left panel shows the relation among measured quantities ($M_{HI}/D^2$, $D_{HI}/D$, where $D$ is the distance to the galaxies), while the right panel shows the relation after the distance has been used to derive linear diameters and masses of the galaxies. The most obvious effect is the change of slope towards the value of 2.

Figure 5.9— Warp asymmetry (in percentage) vs. mean HI surface density. Filled circles indicate bona fide warped galaxies. Warps seem to be more asymmetric in galaxies with low Mean HI surface densities. Each galaxy is identified by its UGC number.
of some warps suggest that their origin is not simply the result of interactions with the environment. The fact that all galaxies with an HI layer more extended than the optical show warps of very different amplitudes could indicate that warping is similar in a way to spiral structure. Most perturbations of a disk galaxy, arising e.g. from companions or secondary infall, will provoke a warped response (just as they excite spiral arms).

The universality of this response makes it hard to pinpoint the perturbation that preceded it. While the trend with environment suggests that tidal effects play an important role, it seems likely that there are other, perhaps more intrinsic, effects at work that cause even quite isolated galaxies to warp.

Debattista & Sellwood (1999) showed by means of N-body simulations that the slewing of a dark halo surrounding a disk galaxy creates a warp. The different response timescale for the realignment of the disk at each radii is responsible for the differential bending in this model. Substructure in the halo will also influence galactic disks, and it is likely that the outer edges of disks, where the selfgravity is weak and timescales are longer will develop warps.

Late infall of HI gas could also be responsible for the warps we detect. This would explain the ‘extra’ HI gas that warped galaxies have outside $R_{HI}$ while the inner profiles of warped and non warped galaxies are similar. This late infall might cause star formation at the outskirts of the optical disk that could be detected in H$\alpha$ imaging or by looking at its color.

To summarize, we list the main conclusions of this chapter:

- We detect warps in 20 out of our 26 sample galaxies confirming that warping of the HI disks is a very common phenomenon in disk galaxies. In fact all galaxies that have an HI disk more extended than the optical are warped.

- The amplitude of warps varies considerably from galaxy to galaxy. Also for a given galaxy there can be a large asymmetry in amplitude and shape between the two sides. A large number of warps in our sample are asymmetric. Most of the galaxies with both sides warped are antisymmetric (S shape warps). We only have two cases of U-type warps, and both galaxies are strongly interacting with nearby companions and are very disturbed.

- The warping of the disks usually starts near the edge of the optical disk where the HI density drops down.

- The connection between HI and optical warps is not clear. HI warps are found in general at larger radii than the optical ones, and as a consequence they probe a different region of the potential of the galaxy.
A joint optical+HI study of warps could give important insights on the formation mechanism(s) of warps.

- There seems to be a dependence of warps on environment in the sense that galaxies in rich environments tend to have larger and more asymmetric warps than galaxies in poor environments.

- The presence of density lopsidedness (and in a weaker way that of kinematical lopsidedness) seems to be related to the presence of nearby companions.

Acknowledgments

IGR wishes to thank Jorge Jiménez-Vicente for many stimulating discussions and useful suggestions. We are grateful to Martin Vogelaar and Hans Terlow for help and assistance in the GIPSY software package. The Westerbork Synthesis Radio Telescope is operated by the Netherlands Foundation for Research in Astronomy with financial support from the Netherlands Organization for Scientific Research (NWO). This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.