Chapter 7

Summary and Future work

This thesis has investigated the distribution and kinematics of gas that is offset from the plane of its host galaxy. This research was brought forth by the discovery of a large amount of neutral hydrogen surrounding the disk of the edge-on galaxy NGC 891 (Swaters et al. 1997; Oosterloo et al. 2007). Because it is the best known galaxy with a halo surrounding its disk, a large part of this thesis deals with NGC 891. The kinematics of the neutral hydrogen gas in NGC 891's halo shows a very interesting feature. It rotates slower the further we look away from the central disk (Fraternali et al. 2005). This is called *lagging*.

Before we started the research for thesis NGC 891, NGC 2403 and NGC 5775 were the only galaxies where this lagging was proven unambiguously (Swaters et al. 1997; Schaap et al. 2000; Lee et al. 2001) but during the course of this research several others were found to be lagging (Barbieri et al. 2005; Westmeier et al. 2005; Boomsma et al. 2005).

The exact origin of this gas remains a mystery up to today. It was suggested that the gas was brought up from the plane by energetic events such as supernovea (Shapiro & Field 1976; Bregman 1980; Norman & Ikeuchi 1989) and therefore ballistic models were investigated to reproduce the lag observed in these halos (Collins et al. 2002; Fraternali & Binney 2006). Even though the models can produce a lag in the halo of a disk galaxy with a reasonable energy input, they consequently underestimate the observed vertical gradient in several galaxies (Fraternali & Binney 2006; Heald et al. 2007).

To get a better understanding of the origin of the gas in the halo we investigated several galaxies using deep HI observations. Here we will summarize the conclusions of this thesis. We start with NGC 891 (§ 7.1) and two other galaxies that were investigated (§ 7.2 and § 7.3). We will end our summary of this thesis with the vertical distribution of a sample of galaxies in § 7.4. In the last section we will present some suggestions for future work which can lead to a better understanding of the extra-planar gas in disk galaxies.

7.1 NGC 891

7.1.1 Ionized gas

In Chapter 2 we present Fabry-Pérot Hα measurements of NGC 891. Even though the lag has been observed in the neutral gas (Fraternali et al. 2005) as well as in parts of the ionized halo (Heald et al. 2006) this is the first time kinematical data of the ionized gas (Hα) are presented covering the whole NGC 891's halo.

In these observations an extra-planar component of ionized gas can clearly be detected. This vertical extent of the Hα emission is already visible in the separate channel maps of our Fabry-Pérot measurements and becomes even more obvious when we add all the channels into a so-called velocity integrated map.

This integrated velocity map shows a clear contrast between the distribution of the Hα on the North-East and the South-West side of the galaxy. This dichotomy is not restricted to the plane of the galaxy but is also clearly visible above the plane. The relation between this dichotomy, the star formation rate (SFR) in the plane, and dust absorption will be presented in § 7.1.2

For the interpretation of the kinematics of the extra-planar gas we constructed several 3-D models of an exponential disk rotating with a rotation curve derived from the HI data (Fraternali et al. 2005). In these models a uniform dust layer is included. This 'dust' disk is defined by the the density of the dust or optical depth which is a user supplied parameter. The disks are distributed exponentially in radius and height and truncated at a specific radius.

When we model NGC 891 with the same scale length for the dust disk as the Hα disk ($h_{\rm g} = h_{\rm d} = 5$ kpc) we obtain a set of models that generate too much intensity at large radii and high velocities when compared to the data. To overcome this problem we modeled the galaxy with a dust scale length of 8.1 kpc, as derived by Xilouris et al. (1998) from observations in the V-band. The longer scale length of the dust reduces the intensity of the gas at large radii and high velocities. This also provides us with a upper limit scale length of the ionized gas of 6.5 kpc since models with a longer scale lengths would reintroduce the high intensities found in the models with equal scale lengths. A lower limit is found for a model with a scale length of 2.5 kpc. This lower limit is set by the fact that models with even shorter scale lengths underestimate the intensity at large radii. Better constrains on the scale length of the ionized disk could be obtained if the truncation radius of the dust disk is known.

When we fit models in this range of scale lengths to the Position Velocity-diagram (PV-diagram) of the major axis we find that the best fit is a model with a central attenuation of $\tau_{\rm H\alpha} = 6$, a cut off radius $R_{\rm max} = 14$ kpc and a scale length and height of 5.0 kpc and 0.8 kpc respectively. With this model we can obtain a first estimate of the lag in the ionized gas by comparing PV-diagrams above the plane to this model. We then construct models with a vertical gradient close to the initial estimate. In this way we confirm the lagging of the halo, as found by Fraternali et al. (2005) and Heald et al. (2006), and determine that this lagging occurs with gradient of $\sim 18.8 \pm 6.3$ km s^{-1} kpc^{-1}.

In the PV-diagrams we also see that compared to the models the distribution of the Hα is displaced to larger radii or lower rotational velocities. This effect increases as we look higher above the plane. This behavior implies that the rotation curve rises less steeply the higher we look above the plane. This effect can be confirmed by comparing three PV-diagrams along and parallel to the minor axis. When we normalize these PV-diagrams we can clearly see that the Hα at a distance of 75 $''$ from the center has a larger gradient than the Hα at 150 $''$ from the center.

7.1.2 Dust

The previously mentioned dichotomy between the South West side and the North East side of NGC 891 manifests itself much stronger in the Hα emission than in emission from other wavelengths. We quantitatively analyze this asymmetry at several wavelengths, thus tracing different components from the galaxy. We determine the ratio of asymmetry at different wave lengths by dividing large strips on the North East side by the same area on the South West side of the galaxy. From this analysis it is immediately obvious that star formation tracers affected by dust attenuation (e.g., Hα, UV) show a much larger asymmetry than star formation tracers unaffected by dust attenuation (24 μm, radio continuum). We also see that the other components in the galaxy, like the old stellar population (3.6 μm) and the neutral gas (HI) are only slightly asymmetric.

Assuming that 24 μm emission from star forming regions dominates in the plane, the 24 μm emission has a direct correlation with star formation (Calzetti et al. 2005). The small asymmetry we find in the 24 μm emission is confirmed by the result found in the radio continuum (Dahlem et al. 1994), which leads us to believe that 24 μm is indeed a good tracer of star formation in NGC 891. Therefore, the asymmetry in Hα is most likely caused by dust in and above the plane.

To provide a possible explanation for the additional asymmetry in wavelengths affected by dust absorption we construct a simple symmetric model for NGC 891. This model is based on the trailing spiral arm idea. In the picture of trailing spiral arms the HII regions are located in front of the dust lanes in the spiral arm. We assume that the emission from the ionized gas is located in and above these HII regions but that the dust distribution in the halo is much more isotropic over the disk. This would lead to a longer sight line through the dust towards the Hα emission on the South West side of the galaxy.

From this model we can derive the additional attenuation (τ_{add}) in the halo caused by the dust between the location of the spiral arms. We see that only at heights $\sim 40''$ (1.9 kpc) the additional attenuation of Hα emission becomes negligible. This is either caused by the absence of dust at this height or by the distribution of the ionized gas becoming such that our lines-of-sight toward the ionized gas become equal on both sides. In this last hypothesis the attenuation by dust, and thus the amount of dust, in the halo is even higher above the plane than derived from our simple model.

Common wisdom still has it that extinction in galaxy disks is predominantly in the plane of the galaxy. Typical scale heights for the dust distribution are much smaller or similar to those for the stellar distribution (Xilouris et al. 1999; Bianchi 2007; Seth et al. 2005). This thesis shows that there is a second spatial component to the dusty ISM with a much more extended scale height which can still cause non-negligible attenuation.

If our view of NGC 891 is correct then the unattenuated Hα emission above the plane is closely correlated with star forming regions in the plane. This implies that the ionized halo gas is mostly brought up from the plane through processes related to star formation. Furthermore the distribution of the attenuating dust above the plane is much more isotropic, and therefore more stable, than that of the ionized gas. This is probably caused by the ionized gas cooling down and recombining before it reaches this stable configuration.

7.2 UGC 1281

In Chapter 4 we presented 21 cm and Hα emission of the edge-on dwarf galaxy UGC 1281. This is the first time such deep HI and Hα observations have been presented for a dwarf edge-on.

The Hα was observed with the Integral Field Spectrograph (IFU) PPAK. IFU's enable us to take optical spectra at multiple positions in a galaxy in one exposure. This way it becomes possible to construct data cubes in the optical in the same way as in the radio. This brings along the big advantage of much higher spatial resolutions in the optical. With this specific set of spectra we are able to reconstruct the kinematics of the Hα emission in UGC 1281.

The integrated Hα velocity map of UGC 1281 shows a non-smooth distribution on the major axis. We can localize several peaks of Hα throughout the disk of the galaxy. One of these peaks is slightly offset from the major axis in the vertical direction. However, It is unclear whether this HII region is actually located in the halo of the galaxy or in the warped outer parts.

The integrated HI velocity map shows a quite regular distribution, with its most remarkable feature: a central depression. This central depression appears symmetrically in position around the center but is much deeper on the North East side of the galaxy. Such a central asymmetric depression is typical for dwarf galaxies.

Furthermore, this map shows that UGC 1281 is warped in its outer parts and this warp resembles a w shape. The maximum deviation from the major axis of this warp is at most 6° in PA. This maximum deviation occurs at about half of the total radius of the HI distribution, the edges of the observed disk deviate less. To put it in different wording, the warp actually bends back towards the main plane of the galaxy in the outer parts.

For the interpretation of the kinematics of the extra-planar HI gas we constructed velocity maps from the Hα and HI data. Also, 3-D models with a modified version of GALMOD are constructed in GIPSY. This modified version enables us to construct kinematic models with a vertical gradient. As a starting point for the HI model we used the observed radial and vertical distribution and a rotation curve obtained from the 1st moment map. Then the model is iterated (by hand) until a best fit is obtained.

After obtaining a model that fits the data in a good manner we see that the rotation curve obtained from these models shows a slow rise in its inner part. This was already seen in velocities obtained directly from the data but there it could still be an effect of the HI distribution or resolution. At about $120''$ the rotation curve flattens off to a maximum rotational velocity ~ 60 km s^{-1}. This slow rise is seen in many dwarf galaxies and thought to be caused by a dark matter dominated mass distribution.

From our modeling we find that our data is not sensitive enough to distinguish between a lagging halo or a line of sight warp. Both models fit the data equally well and there is only a small difference between the input parameters of the models.

In the case of a lagging halo the low vertical extent and the low flux level of the Hα emission would indicate that this extra-planar HI does not originate from galactic fountains but is either infalling primordial HI or brought up from the plane in an interaction with another galaxy.

To obtain the lag in this case we measure the apparent lag in the data by fitting the position of the maxima in normalized PV-diagrams parallel to the minor axis in the data with a straight line. Such a measurement will be affected by beam smearing and the warp and therefore we repeat this measurement for our best fit halo model covering a range in lag. This way we find that the vertical velocity gradient in UGC 1281 in the case of a lagging halo is 8.7$\pm$4.1 km s^{-1} kpc^{-1}.

In the case of a line of sight warp the ionized hydrogen and the distribution of the stars would not extend into the warped region of the disk. However, the scale height in the central parts would be the same for the stars, Hα and HI.

One thing that this analysis makes clear is that great care must be taken to distinguish between lagging halos and line of sight warps. We see that in our models we can go from a lagging halo to a line of sight warp by only adjusting the inclination of the warp by $< 3°$.

7.3 NGC 7814

In deep HI observations of the edge-on Sa galaxy NGC 7814 (Chapter 6) we found two extra-planar features at peculiar velocities. To detect these features we had to reduce the data with a natural weighting function. With a natural weighting function all base lines are considered of equal weight which minimizes the negative inner side lobes of the beam. This improves the visibility of smooth extended structures.* The data reduced in this way clearly shows two features which show an extended vertical distribution and that rotate at velocities higher than the maximal rotation velocity in the disk. These features are distributed symmetrically around the center in the spatial direction as well as their rotational velocities. This gives the impression that they are part of or caused by a rotating structure in the plane of the galaxy. These features add to the wide variety of of extra-planar gas distributions detected in spiral galaxies. As for so many of these extra-planar structures the origin and dynamics of these features remain a puzzle. However, the possible presence of a bar in the center of NGC 7814 might provide some clues to the origin of this gas.

7.4 A small sample of deep HI observations

By combining the previously discussed galaxies with another three galaxies we constructed a sample of 6 edge-on galaxies with deep HI observations. To unambiguously determine the existence of a lagging halo we fitted these galaxies with the tilted ring fitting code TiRiFiC. This way we get the best fit models which we then reproduce with a range of vertical gradients.

For these galaxies we find that 50% of them does have such a lagging halo. For two

* The other common weighting function is Uniform weighting which reconstructs the full resolution of the array

of them (UGC 1831 and UGC 7321) (Matthews & Wood 2003; Oosterloo et al. 2007) this was already known. In the case of UGC 7321 we are able to quantify the vertical gradient to be 15.8± 4.4 km s^{-1} kpc^{-1}. In our sample there is another galaxy (UGC 4704) which appears to be have a lagging halo. This is quite remarkable since this is a dwarf galaxy with hardly any star formation. The vertical gradient here is determined to be 5.3± 0.8 km s^{-1} kpc^{-1}. The other galaxies in our sample show no indication of having a lagging halo.

We searched for possible correlations between the vertical gradient in a galaxy and other properties such as mass, SFR, vertical extent of the gas and Hubble type, but could find no correlation. This is interesting in its own right because if the vertical gradient was solely related to the star forming properties of a galaxy, a clear and obvious trend should be observed between the vertical gradient and the star forming rate of a galaxy. The lack of any other correlation with mass, vertical extent or Hubble type seems to imply that there is not one process that dominates the formation of gaseous halos.

7.5 Discussion and future work

In this thesis we explored the extra-planar gas in a range of spiral galaxies. We investigate three galaxies as individual object and find extra planar gas all three of them. In the dwarf galaxy UGC 1281 we find that this extra-planar gas is either in a lagging halo or in a line of sight warp. In NGC 891 we show that there is not only neutral hydrogen gas that above the plane but also ionized gas and dust. NGC 7814 contains two low level emission features that extend from the plane. These features appear to rotate around the center at velocities higher than the maximal rotational velocities in the galaxy.

We also combined these three galaxies with three others to look at at correlations between the lag in a halo and other properties of the galaxies such as SFR, mass, scale height and Hubble type. No clear correlation could be found not even after the addition of two galaxies known to be lagging.

This work has several implications. First, extra-planar gas can be found in almost any galaxy. Of our small sample of six galaxies with deep HI observations without exception all show some kind of extra-planar gas even though it is not always a lagging halo such as found in NGC 891. However, the sample selection based was to some extend biased by the availability of deep HI observations. All the HI observations used throughout this thesis are equivalent to at least 4×12 hours observations with the WRST. This is a large amount of time to be observe a galaxy and therefore such observations are only done on systems that already show a hint of interesting HI distributions in their outer parts. This of course biases our sample towards galaxies with extra-planar gas.

The fact that we can find no correlation between the galaxies in our galaxy that do show a lagging halo implies that the lagging halo is not predominantly correlated with one parameter. This means that there are more parameters that influence the vertical gradient in a galaxy than just the star formation rate or mass. The fact that the star formation rate is not correlated with the observed vertical gradient means that the lagging gas is not the sole result of galactic fountains or chimneys. Of course, there might be some other parameter that was not investigated by us, such as the halos dust content, that governs the steepness of the vertical gradient.

This shows the need for a larger sample to study lags. One might construct such a sample by obtaining deep HI and Hα observations of galaxies where lags have already been observed. In this sample it would be crucial to cover a range of mass, star formation rates and morphologies. Such a sample should contain significantly more galaxies than the current one.

With the coming of SKA and MUSE it might actually become possible to observe such a large sample to the depths of the observations presented in this thesis in a reasonable time. SKA is the planned Square Kilometer Array which can obtain deep HI observations in manner of hours instead of days. The Multi Unit Spectroscopic Explorer (MUSE) is a second generation VLT instrument. Besides its much higher sensititvity than current day IFU's, It is a wide field integral field spectrograph (Field of View = $1'$ $\times$ $1'$) which will make it possible to observe nearby galaxies with one pointing. This is a significant time reduction for as we have seen in this thesis a small galaxy like UGC 1281 is not even fully covered with three pointings of current day IFU's.

The fact that the dust in NGC 891 extends to large distances above the plane implies that dust absorption cannot always be considered negligible in the outer parts of galaxies. This has to be considered when studying the outer parts in optical emission. Also this has serious implications for the formation of the halo in NGC 891. This dust almost certainly comes from the plane of the galaxy which would mean that certainly a fraction of the gas in the halo comes from the plane. However we have also seen in Chapter 5 that the vertical gradient in the gas does not correlate with the star formation rate. This would mean that either the dust is brought up from the plane by a different mechanism than supernovea or that the gas is a mixture of gas brought up from the plane by supernovae and gas with a different origin. This different origin could easily be infalling primordial gas.

It is unknown how far the dust extends above the plane in NGC 891. Also we do not know whether this is common in halos or that NGC 891 is an exception. To answer these two questions one would need to observe the dust in the lagging halos directly. If one could add dust observations to the previously mentioned sample of galaxies with lagging halos one might be able to answer several questions. First of all it would establish directly how many of the lagging halos also contain dust. Secondly, since the dust comes from the plane of the galaxy it might be used as a tool to determine the amount of hydrogen gas coming from the plane of the galaxy and the amount of gas with a different origin.

This plan has one big caveat, it is extremely hard to detect dust emission directly. Therefore one would have to invent methods that detect dust indirectly in a trustworthy way or find a more efficient way of collecting dust emission. When the Atacama Large Millimeter Array comes online it might actually become possible to study dust in the halos of galaxies directly.

As individual galaxies we can still learn much more from the galaxies NGC 891, NGC 7814 and UGC 1281. NGC 891 is observed to great extent in many wavelengths and since it is relatively close by this galaxy can serve very well as a prototype galaxy with a lagging halo. Therefore it can be used to explore new multi-wavelength techniques for exploring galaxy halos through the means of archival data research with no cost of additional telescope time.

The features in NGC 7814 are puzzling and need to be modeled in detail to determine their spatial distribution and kinematics. The possible existence of a bar in this galaxy also needs to be investigated and if such a bar exists its correlation with the gas features needs further research. More sensitive observations with a higher resolution will be useful for determining the origin of these features. Such observations might be obtained with the Very Large Array since it will not be hampered by its low declination.

The existence of a lagging halo in a dwarf galaxy could be unambiguously shown by deeper observations of UGC 1281 or more detailed modeling of UGC 4704. In this sense the latter seems a more desirable option since our simple analysis already showed that this extra planar gas is most likely in a lagging halo. The existence of such a lagging halo in a dwarf galaxy might have great impact on the theories for galaxy formation and evolution.

To summarize our conclusion in to one overall conclusion: We have deepened the understanding of lagging gas at large vertical distances from the disk of spiral galaxies. This new field of extra-planar lagging gas holds great promise to deepen our understanding of the structure, kinematics and evolution of spiral galaxies.