**rijksuniversiteit
groningen**

The structure and kinematics of halos in disk galaxies

Proefschrift

ter verkrijging van het doctoraat in de
Wiskunde en Natuurwetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. F. Zwarts,
in het openbaar te verdedigen op
vrijdag 7 november 2008
om 13.15 uur

door

Peter Kamphuis

geboren op 14 juli 1979
te Almelo

Promotores: Prof. dr. R. F. Peletier
                          Prof. dr. P. C. van der Kruit

Beoordelingscommissie: Prof. dr. R. -J. Dettmar
                          Prof. dr. K. C. Freeman
                          Prof. dr. J. M. van der Hulst

Did you hear the music?
        A serenade from the stars.
Wake up, wake up
      wake up and look around you.
We're lost in space
      and the time is our own.

Serenade - Steve Miller Band

Cover Image: Peculiar extra-planar HI in NGC 7814 overlayed on top of an composite optical image made with the cfh12k camera at the Canada-France-Hawaii Telescope for the Hawaiian Starlight project (Copyright 2003 CFHT). Background in the back: the Hubble Deep Field (http://hubblesite.org).

Contact information: kamphuis@astro.rug.nl

Contents

Chapter 1

Introduction

Since the dawn of time, men has been looking up at the night sky. At first just with the naked eye, seeing only the white points of light that are so well known to all of us as "stars". When one observes the sky with the naked eye there is only one structure visible in the sky, a long band of whitish light. The Romans baptized this band the "Via Lactea", meaning Milky Way.

When the first vision enhancing instruments became available (glasses, microscopes, telescopes), again men pointed them at the sky. With these simple magnifying instruments most of the "stars" remained unresolved points of light. But when Galilei Galileo pointed his telescope at the majestic band of white light, called the Milky Way, he realized that it actually consisted of many stars that were to faint to resolve with the naked eye.

Already in 1755 Immanuel Kant speculated that this huge collection of stars was a single system kept together by rotation and Newton's gravitational force. Much like our own solar system but on a much larger scale. According to Kant the rotation of the stars would flatten such a system and create a disk like structure. He also suggested that the "Milky Way" is actually only one of many such systems.

With the advancement of technology, telescopes became more powerful and new parts of the electro magnetic spectrum became visible. Every time a new instrument became available it was pointed at the sky and more "stars" were resolved into structures. Scientists found that the sky was laden with nebula, almost as many as there were stars. This started a discussion about scales and sizes in the Universe in the 1920's, which led to the so-called 'Great Debate' between Curtis and Shapley. The main point of discussion was whether nebula were part of the Milky Way or that they were separate systems not unlike the our own Galaxy. The matter was solved when Edwin Hubble resolved individual stars in the nebula M31. By identifying some Cepheid variable stars in M31 he was able to derive a distance to the nebula and establish that it, and many other nebula, was an extra-galactic system.

After settling the 'Great Debate', Hubble inspected many photographic plates of nebula. He found that they could be split up in two different main classes, ellipticals and spirals (Hubble 1926). He then divided these classes into subclasses and this classification scheme is still in use today as the 'Hubble tuning fork diagram' (See Fig 1.1).
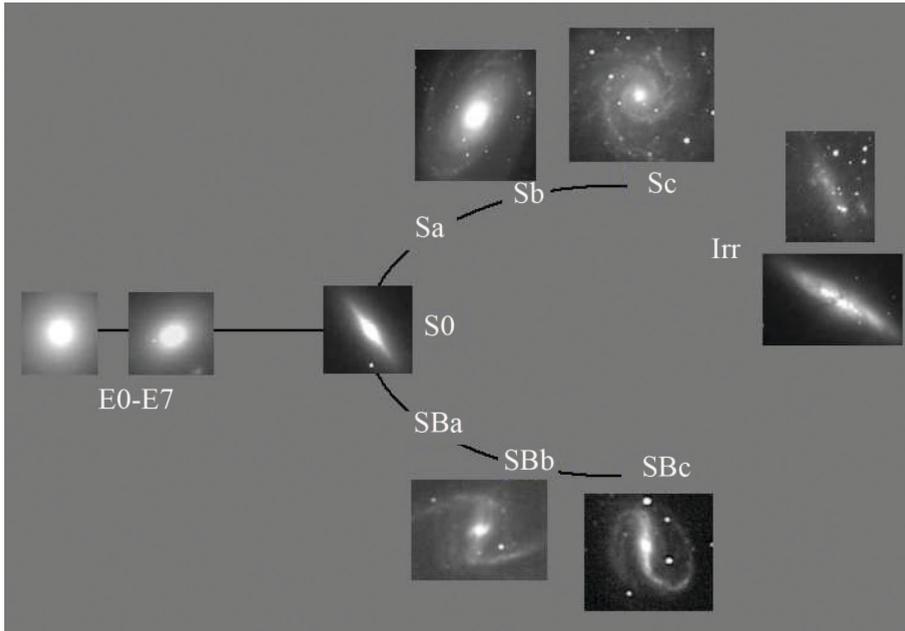
Figure 1.1: Hubble tuning fork diagram. Diagram taken from Ganda (2007).

Even though Hubble based his scheme purely on morphological arguments we now know that there are real structural differences between elliptical and spiral galaxies. Elliptical galaxies are systems where the stars are organized into large spheres and they are supported against gravitational collapse by the random orientations of the orbits of the stars. They are said to be pressure supported because, even though a single star is on a regular circular or elliptical orbit, there is no meaningful structure to the collection of stars. On the other hand, spiral galaxies are systems where the orbits of the stars are mostly ordered into a disk like structure. These systems are said to be rotationally supported because the rotation of the disk counteracts the gravitational force and thus keeps it from collapsing.

Spiral galaxies are mostly known for their name giving feature, their spiral arms. These spiral arms often create the spectacular images of spiral galaxies that do so well at capturing the imagination of almost any one. However, they are no more than a pertubation of the basic structure of a spiral galaxy.

Halfway through the 20th century spiral galaxies were thought to consist of two components. A disk, in which the spiral arms formed, and a spheroid in its center, called the bulge. This bulge varies in size from galaxy to galaxy and can be as big as the disk itself or completely lacking (See Fig. 1.2). The disk was thought to be mostly made of neutral hydrogen gas and young stars.

In the early 1900's Jacobus Kapteyn found evidence that the proper motions of the stars were not random, as was the general view in that time. Surprisingly, the stars could be divided into two streams, apparently moving in opposite directions. This led to the discovery of galactic rotation by Oort and Lindblad several years later. However,

these observations were limited to the neighbourhood of the Sun due to the absorption of stellar light in the plane of the Galaxy by interstellar dust.

When in 1940 Reber mapped the Milky Way in radio waves, Oort realized that a spectral line in the radio would not suffer from extinction by dust. Therefore, the Doppler shifts of such a line, if available, could be used to map the structure of the Milky Way. Another Dutch astronomer, van de Hulst, found that such a line was indeed available. In its ground state, neutral hydrogen (HI), the most abundant element in the Universe, has a hyperfine transition that would emit photons with a wavelength of 21 cm. This led to the construction of the Dwingeloo Radio Telescope and the Westerbork Radio Synthesis Telescope.

Since this discovery Radio Astronomy has become a large part of modern observational astronomy. Especially spiral galaxies were observed in the 21 cm line because most of the neutral hydrogen in the Universe is contained in their disks. Radio observations of spiral galaxies have answered many questions but also brought many new puzzles about the structure of our Universe and its galaxies.

These observations and others in different wave lengths have shown that spiral galaxies are much more complex than just a disk and a bulge. Other components were discovered such as a thick disk consisting of old stars and a halo of stars. Also it became clear that the bulge is not always a separate component from the disk but can be a irregularity that is part of the disk. With radio observations things became even worse. When the first external spiral galaxies were observed in HI it became clear that the neutral gas in spiral galaxies often extended much further out than the optical disks. Not only that but also it became clear that the gas outside the optical disk often deviated from the regular disk stucture observed in the optical.

Besides obtaining structural information about the gas distribution in spiral galaxies, HI observations also provided us with kinematical information about spiral galaxies. Through the observations of the Doppler shift in HI it has become possible to construct rotation curves of our own and other galaxies. These observations showed that galaxies rotate faster than would be expected from the mass of their luminous components. Indicating that galaxies either contain large amounts of unseen matter (Dark Matter) or that our understanding of gravity on galactic scales is incomplete.

This thesis will focus on the, so-called, extra-planar gas, i.e hydrogen gas deviating in the vertical direction from the regular disk. Mostly through the analysis of neutral or ionized hydrogen observations but also by making use of the fact that nowadays observations are done over the whole of the the electro magnetic spectrum. This makes it possible to study astronomical objects in multiple wavelengths, the so-called multi wavelength analysis. Such an analysis enables us to look at different components of a galaxy at the same time.

Much of our current day knowledge about the structure and especially the vertical structure of spiral galaxies has been derived from observations of so called edge-on galaxies where the disk is seen on its side (See Fig 1.2). Before outlining the goals of this thesis and providing a short description of its contents we will discuss the current knowledge about the structure of spiral galaxies and the halos surrounding them in particular.
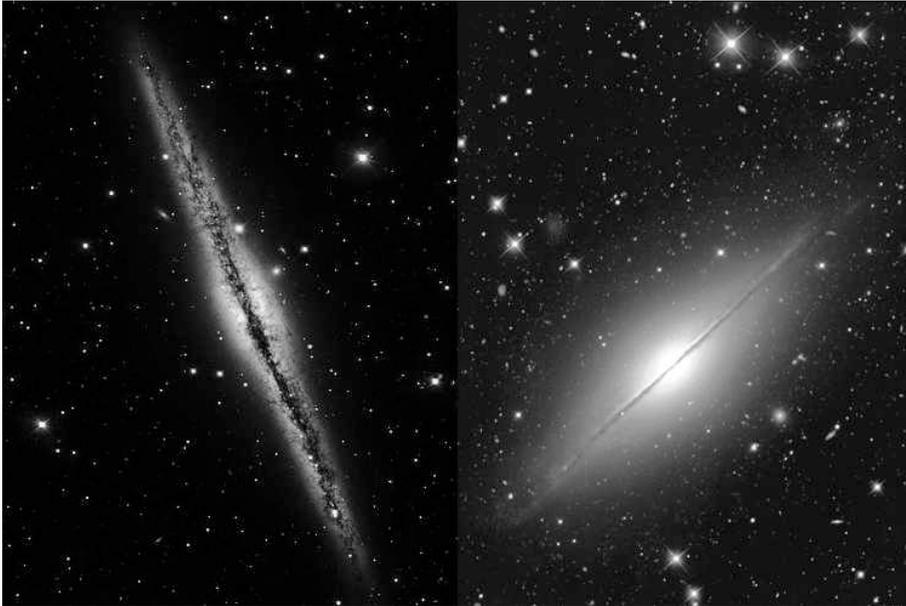
Figure 1.2: Composite optical images made with the cfh12k camera at the Canada-France-Hawaii Telescope for the Hawaiian Starlight project. Left: NGC 891 Right: NGC 7814

1.1   Background

The fact that the Universe is immense and that spiral galaxies are randomly distributed over the sky in position and orientation, greatly helps us when we want to study certain aspects of spiral galaxies. If we want to study the vertical structure of spiral galaxies, like in these Thesis, we can select spiral galaxies of which the disk is orientated in such way that we look exactly at its side. Galaxies that are orientated in this way are normally referred to as edge-on galaxies.

In a mathematical way this orientation is defined as the angle between the disk and the plane of the sky; This angle is called the inclination of a galaxy (i). In the case of a perfectly edge-on galaxies this angle is $90°$. In the opposite case ($i = 0°$) the disk is seen from the top. These galaxies are called face-on galaxies in astronomy.

Observing galaxies that are heavily inclined brings many advantages. Due to the edge-on orientation the light at a single point in the disk is summed with the whole of the disk in front and behind it. This fact makes that irregularities in the disk are smoothed out and that the luminosity is amplified over the whole disk. Therefore, edge-on galaxies are extremely suitable for studying the faint outer parts of spiral galaxies.

Another great advantage is that in these galaxies it is relatively easy to study the vertical structure of galaxies. In galaxies less inclined, it becomes increasingly hard to study the vertical structure of galaxies because our line of sight cuts through these galaxies in the radial as well as the vertical direction. This will either block the stellar light from the lower layers by dust extinction, or mix all the radiation coming from different heights in the galaxy. In edge-on galaxies such confusion is avoided in the vertical di-

rection and since the light is naturally amplified one can trace the vertical structure to large distances from the plane.

A great disadvantage of the edge-on orientation is that not only the light from the stars in the whole disk becomes summed, but also the extinction due to dust. This can often obscure the whole plane of the galaxy. This effect creates the great dark lanes often seen in optical images of edge-on spiral galaxies (See for example Fig 1.2).

Because of the advantages of the edge-on orientation, edge-on galaxies were the natural place to search for the end of the disk. The end of the disk can place important constraints on theories for disk evolution and formation. This might be the place where the enviroment in the disk is no longer suitable for star formation (Fall & Efstathiou 1980; Kennicutt 1989) or it may be caused by the maximum specific angular momentum of the material that initially formed the galaxy (van der Kruit 1987). The end of the disk is determined by the so-called truncation radius. At this radius the light distribution suddenly shows a much steeper drop than the gradual decline found inside the truncation radius. This truncation radius is now observed in 60% of the edge-on systems (van der Kruit & Searle 1982; Kregel et al. 2002) as well as less inclined systems (Pohlen & Trujillo 2006).

It has been shown that the gradual brightness decline before the truncation radius is best described as an exponential in the radial direction (de Vaucouleurs 1959; Freeman 1970). In modern astronomy this exponential is described by one parameter, the scale height. This scale height is the distance over which the luminosity distribution drops by a factor of e. In nearby spiral galaxies the scale length can range from 1 to 20 kpc depending on the overall size ,i.e. mass, of a galaxy (Graham 2002).
If the luminous matter traces the mass in a galaxy, something that seem to be implied by the fact that the color of a galaxy is almost constant over its radius (de Jong 1996), this would mean that the exponential shape is inbedded in the mass distribution of the galaxy. Therefore it seems to be an intrinsic shape of spiral galaxies which is either established when the galaxy first formed (Fall & Efstathiou 1980; Dalcanton et al. 1997) or later by a redistribution of matter caused by infalling gas (Lin & Pringle 1987; Thon & Meusinger 1998).

In the vertical direction the luminosity can also easily be resembled by an exponential. The e-folding of this exponential, described by the scale height, is usually related to the scale length and is typically ten times smaller (van der Kruit & Searle 1982; Shaw & Gilmore 1989). Even though over the radial extent of a galaxy the luminosity density, and thus the mass density, can drop easily by four orders of magnitude, the observed scale height remains remarkably constant over the extend of the disk (van der Kruit & Searle 1981a) . An exception seems to be found in early type galaxies where a small increase, called flaring, can be observed (de Grijs & Peletier 1997).

In more massive spirals the scale height of the dust is normally much smaller than that of the old stars. This effect gives us the clear dark lanes over optical images of edge-on galaxies (See fig 1.2). However, in smaller galaxies this effect is often missing. This is because the dust disks in these small galaxies are much more puffed up compared to the ones in their massive ($v_{rot} > 120$ km s^{-1}) counter parts (Dalcanton et al. 2004).
After this general overview about the structure of spiral galaxies we will now take a closer look at one specific edge on system.

1.1.1 NGC 891

One of the best studied edge-on galaxies is NGC 891 (See Fig.1.2, left). It was first thought to be remarkably similar to the Milky Way and thus provided an excellent case to study the structure of massive spiral galaxies without the problems caused by being inside the system. It is a galaxy at close proximity (9.5 Mpc, van der Kruit & Searle (1981b)) from our own Milky Way and highly inclined (89.8±0.5°, Kregel & van der Kruit 2005). Because it is, on Universal scales, so near to our own Milky Way it can be studied in high detail. Therefore, it has been observed at many wavelengths ranging from the UV to the Radio (Allen et al. 1978; Sancisi & Allen 1979; van der Kruit & Searle 1981b; Dahlem et al. 1994; Swaters et al. 1997; Xilouris et al. 1998; Howk & Savage 2000).

van der Kruit & Searle (1981b) were the first to observe the vertical structure of NGC 891 in the optical at great detail. They found that the light distribution of the disk was easily fitted by a model consisting of an exponential drop off in the radial direction and the z-dependence of a locally iso-thermal sheet. Later, these observations were confirmed by Xilouris et al. (1998) who fitted the light distribution with the double exponential,

$$L_{disk}(R, z) = L_0 e^{(-\frac{R}{h} - \frac{z}{z_0})} \tag{1.1}$$

Where L is the luminosity, L_0 the stellar emissivity at the center of the disk, R the radius, h the scale length, z the height and z_0 the scale height. They used the same double exponential to fit the extinction in the disk, thus in a manner of speaking the dust disk. From the fitting of this model they found that NGC 891 is best described by a stellar disk with a scale height of 0.39±0.01 kpc and a scale length of 5.71±0.2 kpc in the V-band. In the optical NGC 891 looks like a normal edge-on galaxy.

Allen et al. (1978) and Dahlem et al. (1994) observed NGC 891 with high resolution and high sensitivity in radio continuum emission and found a large radio halo around NGC 891. This radio halo was brighter on the North East side of the Galaxy than in the South West. Also the emission caused by ionized hydrogen, Hα emission, was detected up to large distances from the plane (Dettmar 1990; Rand et al. 1990). This extended layer of diffuse ionized gas (DIG) in NGC 891 (z_{NW}=0.5 kpc, z_{SE}=0.3 kpc, Dettmar (1990)), is thought to be similar to the extended layer of DIG, or Reynolds layer, (Reynolds 1990) of the Milky way (Dettmar 1990; Rand et al. 1990). In these Hα observations the asymmetry is even more pronounced than in the radio continuum.

Hα and radio continuum emission are considered to be tracers of the star formation in a galaxy. This idea has led people to believe that the star formation in NGC 891 is heavily lopsided (Dahlem et al. 1994; Howk & Savage 2000). Even though this makes the galaxy highly interesting the real suprise is still to come.

Sancisi & Allen (1979) observed the HI distribution and kinematics of NGC 891 with the newly build Westerbork Radio Synthesis Telescope (WRST). They found a heavily lopsided HI disk that on its outer radii had some extensions out of the plane. They interpreted this as a flare, in which the gas on the outer edges of the disk has higher scale heights due to the lower gravity in the plane.

When Swaters et al. (1997) re-observed the HI they found that a flare could not explain the hydrogen distribution above the plane but that instead the extra planar gas was in the halo of NGC 891. By comparing the the galaxies HI images at different velocities (channel maps) with models the concluded that the extra planar gas was rotating slower

than the gas in the plane; This behaviour is called the lagging of the gas. The lagging gas in the halo of NGC 891 is thought to be similar to the extra planar gas in the Milky Way.

The latest HI observations of NGC 891(Oosterloo et al. 2007) are some of the deepest HI observations ever done on a single galaxy. These observations show a massive neutral hydrogen halo around the galaxy that is lagging with a vertical gradient of $\pm$ 15 km s^{-1} kpc^{-1}. This gradient is also seen in Integral Field Unit observations of the DIG in a part of the halo (Heald et al. 2006).

Nowadays NGC 891 has become a classical example of a galaxy with a halo and has raised a great interest in the structure and kinematics of halos in disk galaxies and extra planar gas.

1.2 Extra-planar gas

Extra-planar HI gas was discovered quite early on, in our own Milky way in the form of High Velocity Clouds and a warp in our own Milky Way (Burke 1957; Kerr & Hindman 1957) and as warps in external galaxies (Rogstad et al. 1974).

Halos and warps form the two most important forms of extra planar gas. Therefore we will discuss them in some more detail below.

1.2.1 Warps

(Sancisi 1976) found many systems with a vertical deviation of the gas compared to the inner disk of a spiral galaxy. Such a deviation is called a warp. The most extreme warp in an edge-on system was observed by Bottema et al. (1987) in NGC 4013 (See Fig. 1.3, Left). In an edge-on system it is easily seen what a warp exactly is. However, warps are also observed in less inclined systems by fitting a so-called Tilted Ring model to the velocity fields of these galaxies. In this model a galaxy is resembled by a number of rings that in the outer parts are inclined compared to the inner rings (See Fig 1.3, Right). It has been shown that warps are very common in disk galaxies (Sancisi 1976). In fact García-Ruiz et al. (2002) claimed that *"all galaxies that have an extended HI disk with respect to the optical are warped"*. They made this claim based on HI observations a sample of 26 edge-on galaxies in the Northern hemisphere.

Briggs (1990) defined a set of rules for the behaviour of warps in galaxies based on a set of existing observations. Two of these rules being *"The HI layer typically is planar within R_{25}, but warping becomes detectable within $R_{\mathrm{Ho}} = R_{26.5}$."* and *"Warps change character at a transition radius R_{Ho}"*. Where R_{25} denotes the radius at the 25th B-band magnitude of the galaxy, $R_{26.5}$ the radius at the 26.5th B-band magnitude which is also called R_{Ho}, the Holmberg radius.

In the early days people thought that warps were caused by interactions with other galaxies. However it soon became clear that warps are also quite common among isolated galaxies. This formed a problem for this theory of warp formation because warps were not thought to be long lived. A different theory for the origin of warps is that they are formed through the continuous infall of Inter Galactic Hydrogen gas that has a different angular momentum.

If this gas had angular momentum such that it would end up at radii within the
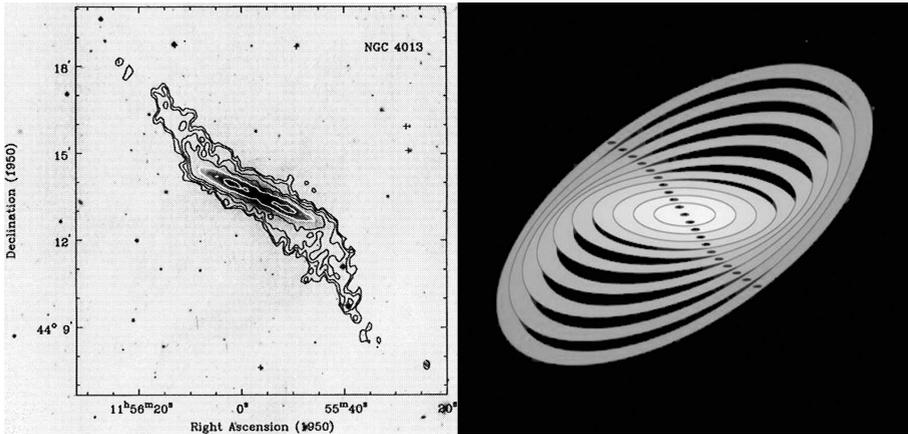
Figure 1.3: Left:Integrated moment map of NGC 4013. (Bottema et al. 1987). Right
:Tilted ring model of a galaxy from García-Ruiz (2001)

massive, already formed, extremely stable optical disk it would be flattened into a reg-
ular disk aligned with the already existing disk through gravity. However, if the initial
angular momentum of the accreting material is such that it virializes at radii larger than
the initially formed disk, gravity would not be able to align the plane of rotation with
the already existing disk (van der Kruit 2007).

A second possibility is the misalignment of the dark halo with the disk. In this case
it is thought that the gas on the outer edges of the disk is more under the influence of
the Dark halo and therefore tends to align with it (Debattista & Sellwood 1999). This
could also cause a long living warp. Another possibility is that warps are induced by the
magnetic field in galaxies (Battaner et al. 1990)

The warp often starts at the truncation radius of the optical disk and the onset
is abrupt and discontinuous (van der Kruit 2007). This behavior has important impli-
cations for the origins of warps but also the origin of the truncation radius because it
implies that the warp has been formed after the initial disk. If this is the case then
the truncation radius is determined by the maximum specific angular momentum of the
proto-galaxy (see § 1.1)(van der Kruit 2007).

If the warping of the plane took place exactly along the line of sight it would become
very hard to distinguish it because it would only look like a thickening of the plane. Such
a thickening could also be explained by flaring of the outer rings or a halo. Which brings
us back to NGC 891 where the extra planar gas was initially thought to be in a flare.

1.2.2   Halos

The discovery of a very extended HI halo in NGC 891 (See 1.1.1) has initiated a new
field of astronomy of halo kinematics and structure. After the initial studies conducted
on NGC 891 many other studies have followed studying the frequency, kinematics and
structure of halos in spiral galaxies (Schaap et al. 2000; Lee et al. 2001; Rossa & Dettmar
2003; Barbieri et al. 2005; Westmeier et al. 2005; Boomsma et al. 2005).

These studies have shown that NGC 891 is not the only galaxy with an halo. Based on a large Hα survey of edge-on galaxies Rossa & Dettmar (2003) found that in about 40% of the galaxies in their sample there is a clear detection of extra-planar DIG. They investigated the morphological appearance of these halos and classified them accordingly. Together with several Hα imaging studies of individual objects it has now been shown that ionized halos appear in many forms.

Ionized halos have been found that consist of thick layers with filaments and bubbles (NGC 4631, NGC 5775) (Dettmar 1990; Rand et al. 1990; Pildis et al. 1994b; Hoopes et al. 1999; Miller & Veilleux 2003)as well as ones which show only individual filaments and isolated plumes (e.g., UGC 12281)(Rossa & Dettmar 2003). However, only in a few of the observed galaxies their is evidence for widespread eDIG in the halo comparable to that in NGC 891.

The origin and ionization source of the DIG component as well as the origin of the neutral extra-planar gas is still a puzzle. Determining the origin of this gas can provide important constraints for models of the inter stellar matter (ISM) in general and on the large-scale exchange of matter between disk and halo in particular (e.g., Dettmar 1992; Rand 1997).

The lagging behaviour seen in the Halo of NGC 891 is also observed in other galaxies in HI (Fraternali et al. 2005; Swaters et al. 1997) as well as in Hα (Rand 1997; Heald et al. 2007). For theoreticians this lag is the greatest challenge to explain about the observed halos.

Current theoretical models try to explain the formation of the halo gas by means of galactic fountains (Shapiro & Field 1976; Bregman 1980; de Avillez & Breitschwerdt 2005) and chimneys (Norman & Ikeuchi 1989) (See Fig 1.4). In these models the gas in the halo is brought up from the disk by supernova explosions of massive stars or even complete clusters of stars in the plane exploding at the same time. Due to the force of the explosion, gas is pushed away from the origin of the explosion. Initially this happens in the form of an expanding sphere (See Fig 1.4). However, because the explosion takes place in the disk, the pressure in the vertical direction is much less. Therefore, the explosion can push the gas in the vertical direction without losing much energy and chimney like tubes will form in this direction. Thus blowing gas from the plane into the halo.

Based on these theories people have tried to explain the lag with ballistic models (Collins et al. 2002; Fraternali & Binney 2006). In these models little clouds of HI are shot out of the plane. The initial speed is related to the star formation in the galaxy. Then by following the gravitational motion of the clouds and shooting up new clouds continuously they obtain a halo structure in their model. Fraternali & Binney (2006) are able to reproduce the vertical HI distributions of NGC 891 and NGC 2403 this way. However, their model fails in two important aspects: (1) they do not reproduce the right gradient in rotation velocity; (2) for NGC 2403 they predict a general outflow where an inflow is observed.

A different approach to the problem was taken by Barnabè et al. (2006). They investigated hydrostatic models and were able to reproduce the lag observed in the halo of NGC 891. However, the stability of these models remains unresolved.

These models all assume that the gas in the halos comes from the disk of the galaxy. This is of course not necessarily true. As we have seen with the warps, gas can be accreted onto galaxies. This gas could also form the halo of a spiral galaxy. Especially, when a small halo would already be present formed in the way previously discussed.
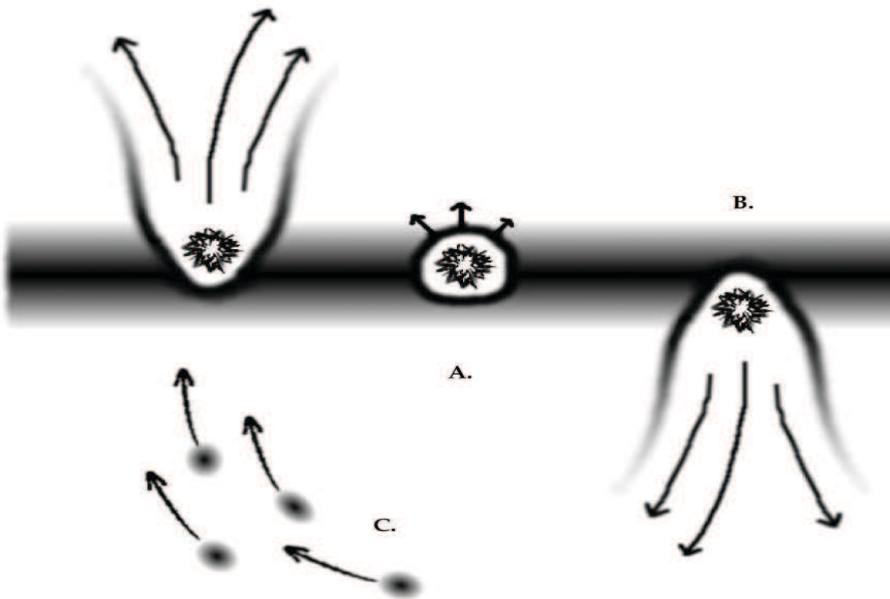
Figure 1.4: Schematic of the galactic fountain/chimney model from Boomsma (2007). A) The initial supernova explosion forms a expanding bubble in the disk. B) Due to the lower pressure in the vertical direction the bubble mainly expands into this direction and blows hot gas into the halo. C) the gas cools down and rains down onto the disk as neutral hydrogen

1.3   This Thesis

1.3.1   Goals & Outline

Even though by now many edge-on galaxies have been observed through the whole of the electro magnetic spectrum only a handful of them have been observed to a depth that extra-planar gas could be analyzed kinematically. We have strong indications that extra-planar gas is common in spiral galaxies. However, how common is still unclear. The origin of this extra-planar gas in spiral galaxies is also still a puzzle.

This thesis aims at finding constraining clues about the origin of extra-planar gas and the frequency at which it occurs. This will be done by analyzing the HI observations of six galaxies which are observed to a depth that extra-planar gas can be detected. These six galaxies are selected to cover a range in galaxy properties. Heald et al. (2007) have investigated a set of 3 galaxies with the aim of finding correlations between the lag and other properties of the galaxies. They found a correlation between the scale height and the lag of these galaxies. However, their sample contained only massive spiral galaxies, where the only reasonably varying parameter was the SFR, and the correlation was weak.

We will extend the general knowledge about extra planar gas by first investigating some aspects of NGC 891 that have been neglected up to now or could greatly use improvement. Chapter 2 will start this thesis by analyzing the diffuse ionized gas in the classic example of a halo galaxy, NGC 891. This chapter will extend the work of Heald et al. (2006) through the analysis of Fabry-Perót measurements over the whole Halo of NGC 891 instead of just a part.

In Chapter 3 we present an multi-wavelength analysis of the same halo. This multi wavelength analysis is done to extend the knowledge of the structure of NGC 891. It focusses on the distribution of the SF in the plane and dust absorption above the by comparing the asymmetry between the North East and South West sides of the galaxy.

Then, in Chapter 4. we will take a close look at the extra-planar gas in a completely different kind of galaxy, the edge-on dwarf galaxy UGC 1281. Dwarf galaxies have not yet been observed with the aim of analyzing the extra-planar gas. Therefore, these observations will extend the range of galaxies where there is observational data with sufficient depth to observed extra-planar gas in the form.

In Chapter 5 we will analyze a set of six galaxies, including NGC 891 and UGC 1281, to look for correlations between the properties of the extra-planar gas and other properties of these galaxies.

Extra-planar gas at peculiar velocities in the edge-on galaxy NGC 7814 will be presented and discussed in Chapter 6 and in the final chapter (Chapter 7) we will summarize and discuss the results of this thesis and the possibilities for future work.