The disk-halo connection in NGC 6946 and NGC 253
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Introduction

The gas in spiral galaxies is concentrated in a flat disk and rotates differentially. In the Milky Way, however, there are gas complexes at velocities and locations that do not fit in the picture of differential galactic rotation. These are called Intermediate-Velocity Clouds (IVCs) and High-Velocity Clouds (HVCs) (Muller et al. 1963; Wakker & van Woerden 1997, and references therein). Their distances, masses and origin are still subject to debate.

Recently, similar gas components with peculiar velocities have also been discovered in other galaxies (Van der Hulst & Sancisi 1988; Kamphuis 1993; Swaters et al. 1997; Schaap et al. 2000; Fraternali et al. 2001; Matthews & Wood 2003; Barbieri et al. 2005). Their origin is still a puzzle, but their masses and (relative) location in the parent galaxy are known. It is hoped that the study of this anomalous velocity gas will also help to understand the HVC phenomenon in the Milky Way.

1.1 The Milky Way: Intermediate- and High-Velocity Clouds

Figure 1 shows the distribution of the HVCs (Wakker 2005). These are the H I clouds with velocities that differ by $\pm 90 \text{ km s}^{-1}$ or more with respect to the velocity expected for regular Galactic rotation. There is also another population at lower velocities, the so called Intermediate-Velocity Clouds or IVCs. The distinction between the two populations is arbitrary and has historical reasons. In general, however, there seems to be a different explanation for the origin of the clouds with the high velocities and those with less deviating velocities, although the nature and origin of both HVCs and IVCs are still being debated. The distance is the main uncertainty. The HVCs may be within a few kpc in the Galactic halo, or at hundreds of kpc in the Local Group. Consequently, also the masses of the clouds are unknown.

Observations of absorption lines in the spectra of halo stars have made it possible to set upper and/or lower limits to the distances of some of the large complexes. These are found to be within 10 kpc from the disk of our Galaxy. The masses are then of the order of $10^{6} M_{\odot}$.
There have also been attempts to determine the metallicities for the HVCs from the absorption line spectra (Van Woerden & Wakker 2004, and references therein). These could tell more about the origin. If a cloud originated from the gas disk of the Milky Way, its metallicity would be close to solar. Very low metallicities point at an extragalactic origin.

For one complex the origin and distance have been well established. This complex is very extended and runs over a large fraction of the southern sky. It is connected to the two companions of the Milky Way, The Large and Small Magellanic Clouds (LMC and SMC) and is, therefore named Magellanic Stream (Mathewson, Cleary & Murray 1974; Putman et al. 1998, see also Fig. 1). Simulations show that this gas has probably been stripped from the LMC and SMC in a passage close to the Milky Way (Murai & Fuljimoto 1980; Moore & Davis 1994; Gardiner & Noguchi 1996; Gardiner 1999; Yoshizawa & Noguchi 2003).

1.2 High-velocity gas in other galaxies

HI gas complexes with large velocity anomalies, similar to the IVCs and HVCs in the Milky Way, have recently been discovered in nearby spiral galaxies (Van der Hulst & Sancisi 1988; Kamphuis 1993; Swaters et al. 1997; Schaap et al. 2000; Fraternali et al. 2001; Matthews & Wood 2003; Barbieri et al. 2005). The advantage here is that distances and masses are known. One of the first galaxies in which gas was found with peculiar velocities was the face-on spiral M 101, where a complex with a mass of a few $10^8 M_\odot$ and velocities up to 160 km s$^{-1}$ was discovered (Van der Hulst & Sancisi 1988). This gas has been interpreted as the result of an accretion event.

In another face-on galaxy, NGC 6946, gas with high velocities was found widespread over the disk (Kamphuis & Sancisi 1993). These motions have components
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perpendicular to the plane and are probably due to the disk-halo interaction where gas is brought into the halo and is falling back onto the disk. It is not known, however, how far this gas is from the disk. For the study of the vertical distribution of H I galaxies with a different orientation are needed.

Edge-on systems have the advantage that the vertical distribution of the gas can be observed directly. Early studies of the nearby edge-on galaxy NGC 891 already revealed H I reaching a few kpc into the halo (Sancisi & Allen 1979; Swaters et al. 1997). In more recent and more sensitive observations of NGC 891 with the Westerbork Synthesis Radio Telescope (WSRT), the H I appears to be even more extended in the z-direction (Fraternali et al. 2004b; Oosterloo et al. 2006). Filaments are seen reaching up to 15 kpc from the disk.

The edge-on orientation also allows the measurement of the rotation velocity of the extra-planar gas. Detailed 3D modelling is necessary to obtain the distribution and kinematics of the H I. From such models it has become clear that the extra-planar H I found in NGC 891 is above the disk and has a slower rotation velocity than the gas in the disk (Swaters et al. 1997; Fraternali et al. 2004b). Observations of other edge-on galaxies such as UGC 7321 (Matthews & Wood 2003), and also less inclined galaxies (see below), suggest that these lagging halos are probably a common phenomenon in spiral galaxies.

Evidence for slowly rotating extra-planar H I comes also from the observations of galaxies of intermediate inclinations. This has first been seen in WSRT (Schaap et al. 2000) and in deep, Very Large Array (VLA) (Fraternali et al. 2001) observations of NGC 2403, a nearby galaxy with an inclination of 63°. A position-velocity diagram from the NGC 2403 data of Fraternali et al. is shown in Fig. 2. This is a slice taken along the major axis of NGC 2403. This plot shows the emission of the rotating H I disk. The lagging halo shows up as a "beard" (Sancisi 2001) on the low-rotational velocity side of the cold-disk emission. The position-velocity diagram in Fig. 3 shows a thin-disk model of NGC 2403. The disk emission is nicely reproduced, but the beard is absent.

In NGC 4559, a galaxy with similar intermediate inclination, a similar H I beard has been observed (Barbieri et al. 2005). Models show that this beard gas is distributed in a thick disk with a height of a few kpc and rotates more slowly than the H I in the thin disk. It is therefore probably the same phenomenon as observed in the edge-on galaxies. Furthermore, analysis of the kinematics of the extra-planar H I suggests a radial inflow.

1.3 Explaining the halo of gas

There is no unique explanation yet for the origin of the extra-planar H I. Two mechanisms seem to play a role: galactic fountains and accretion of gas from intergalactic space.

1.3.1 The galactic fountain

In the galactic fountain mechanism (Shapiro & Field 1976; Bregman 1980) the interstellar medium (ISM) in the disk of a spiral galaxy is heated and swept up by winds from young massive stars and SN explosions (see a sketch in Fig. 4). Winds and ex-
Explosions are thought to create large bubbles in the ISM. The interior of these bubbles is tenuous hot gas. The walls of the bubbles are formed by swept up cold and warm gas, in neutral and ionised state. The bubbles can grow by several generations of star formation (A in Fig. 4).

The density distribution in a galactic disk is stratified in the vertical direction, while it is fairly constant in the plane. An expanding bubble in such a medium will experience less pressure in the vertical direction and will grow faster in that direction.

At some point the bubble has grown higher than about 1 or 2 scale heights of the disk, breaking it and the hot interior is blown freely into the halo (B). The material in the halo will cool after some time and fall back onto the disk (C).

Old, broken bubbles (D) will stay visible as holes in the disk for a while, till random gas motions and differential rotation of the disk have made them disappear. Although the mechanism may seem simple, not much is known about the details. For example, it is still unclear in what state the halo gas is. It is assumed to start as hot, ionised gas. This picture is supported by a study on the kinematics of diffuse ionised hydrogen in NGC 2403 (Fraternali et al. 2004) and some edge-on systems (Rand 1998). A fraction of the outflowing gas, however, can also still be neutral. For
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Figure 3— A position-velocity diagram showing a thin disk model of NGC 2403. (Fraternali 2001).

e example, Kamphuis, Sancisi & Van der Hulst (1991) find an expanding super bubble in M 101 where H I is probably accelerating into the halo. Although it seems to be in the first stage of the galactic fountain, the gas happens to be in the neutral state.

It is unclear whether the extra-planar gas is in dense clumps or in a more diffuse, smooth component. Depending on its exact state the timescale for the gas to remain in the halo is different. If the halo consists mainly of dense clouds, then these clouds will not feel much pressure. They may then follow approximately ballistic trajectories in the halo before they fall back. Studies based on ballistic models show timescales in the order of $10^8$ yr (Collins, Benjamin & Rand 2002; Fraternali et al. 2005). The kinematics, however, seems not compatible with these models.

Although the gas is blown out of the disk, it is expected to still show the large scale kinematics of the underlying disk. The main difference from the gas in the disk is its slower rotation. This agrees with the observations of NGC 4559 (Barbieri et al. 2005) and NGC 2403 (Fraternali et al. 2001).

1.3.2 Accretion

Another mechanism which might produce gaseous halos is accretion of small gas-rich objects such as dwarf galaxies or intergalactic gas clouds (e.g. Oort 1970).
Van der Hulst & Sancisi (1988) report the discovery of gas moving with high speed perpendicular to the disk of the face-on galaxy M 101. They suggest that the high-velocity complexes resulted from recent collisions of large, extragalactic gas clouds with the disk of M 101. A similar feature has been discovered in NGC 2403 (Fraternali et al. 2002b).

Gas from outside a galaxy has probably been only slightly enriched by stellar feedback and therefore will still be metal poor. One of the HVCs in our Galaxy, Complex C, has such low metal abundance. It also has a velocity toward the Galactic Plane. It has been suggested that Complex C is being accreted by our Galaxy (Tripp et al. 2003).

A stellar analogue to this phenomenon is Sagittarius Dwarf (Ibata, Gilmore & Irwin 1994). Stellar streams have been found, suggesting that they originate from a dwarf galaxy ripped apart by the Milky Way (Johnston, Spergel & Hernquist 1995; Ibata et al. 2001). Some may even be connected to HVCs (such as complex A, Belokurov et al. 2006). Similar stellar streams and loops have been found around M 31 (Ibata et al. 2001b; Ferguson et al. 2002).

It is difficult to distinguish between gas from a galactic fountain and accreted gas without knowing their metallicity. When anomalous gas is found in regions without any star-formation activity, for example in the outskirts of a disk, then accretion would seem a more likely explanation than a galactic fountain.
1.4 This study

From previous studies, as mentioned above, we know that extra-planar H\(\text{I}\) is probably common in spiral galaxies. In addition, we know that widespread high-velocity gas exists in NGC 6946. They probably are due to similar phenomena seen from different perspectives. What is still missing is a clear link between the high-velocity gas and phenomena in the disk. Studies of face-on systems are needed to investigate such a relationship. Previous observations, however, lacked sufficient sensitivity. For example, Kamphuis & Sancisi (1993) had to heavily smooth their data to reveal the widespread high-velocity gas in NGC 6946 and this made a detailed study of the distribution impossible.

We therefore have obtained new, deep H\(\text{I}\) observations of NGC 6946 with the upgraded WSRT. These data give us a detailed picture of the vertical gas motions, and enable us to link the distribution of high-velocity gas complexes to local phenomena in the disk. We hope this will help us understand which of the proposed mechanisms is the main drive for the extra-planar gas in spiral galaxies.

We have also observed the H\(\text{I}\) in the nearby starburst galaxy NGC 253 with the Australia Telescope Compact Array (ATCA) to study the effects of galactic fountains in an extreme case of starburst.

1.4.1 NGC 6946

NGC 6946 has a number of properties that make it suitable for the purpose of our investigation. It is a nearby galaxy at a distance of about 6 Mpc, which makes it possible to study the ISM with high spatial resolution. The WSRT has a resolution of about 13”, or about 380 pc. We used 16 × 12 hrs of integration, which enables, at this distance, the detection of H\(\text{I}\) clouds with masses down to \(10^5 \, M_\odot\).

NGC 6946 is almost face-on (inclination is about 38o), so that it is possible to measure vertical motions and to determine where these motions occur. For example, the locations of the star formation in the disk and the high-velocity H\(\text{I}\) complexes can be easily compared.

In light of the galactic fountain, NGC 6946 represents an interesting case. Massive-star formation is seen throughout the disk and H\(\text{II}\) regions have been detected even in the far outer spiral arms (Ferguson, Gallagher & Wyse 1998). Related to the star formation are the SN explosions. In the last 100 years 8 SNe have been observed in NGC 6946, which is the largest number observed in a single galaxy. NGC 6946 seems to have enough ‘fuel’ to maintain a galactic fountain.

Previous studies have shown that NGC 6946 is a gas-rich galaxy with large holes in the H\(\text{I}\) distribution, which point at energetic events. Kamphuis & Sancisi (1993) already found evidence for gas which moves with more than 100 km s\(^{-1}\) with respect to the local rotation of the disk.

The study of the gas kinematics and distribution in NGC 6946 will help to construct the 3D picture of extra-planar H\(\text{I}\) and disk-halo flows in spiral galaxies.

1.4.2 NGC 253

The observations of NGC 253 serve to study the neutral hydrogen in the case of a strong starburst. NGC 253 is the nearest starburst galaxy at a distance of about 3.9
Mpc. It is the largest member of the Sculptor group of galaxies, a neighbour of the Local Group. A galactic wind has blown large super bubbles of hot gas in the halo on both sides of the disk (Pietsch et al. 2000; Strickland et al. 2002).

Besides the starburst in the central region, the level of star formation is high throughout the whole disk. According to the galactic fountain model we would expect a large amount of gas in the halo. This gas might, however, be mostly ionised and not observable as H\textsc{i}. Previous H\textsc{i} observations did not show any sign of H\textsc{i} with anomalous velocities, but were limited in sensitivity.

The inclination angle is 78°, so the observations mainly probe the vertical distribution and the galactic rotation of the gas.

1.5 Structure of this thesis

The major part of this thesis is devoted to the results from the deep H\textsc{i} observations of NGC 6946. In chapter 2 we will give an overview of these results. We will show the distribution of the H\textsc{i} in the disk and present a detailed analysis of the kinematics.

In chapter 3 we examine in detail the properties of the high-velocity gas that we have detected. We compare the distribution of this high-velocity gas to the distribution of young stars, and we discuss the possible origins of the gas.

Chapter 4 describes the holes that are seen in the H\textsc{i} disk. We present a catalogue of the H\textsc{i} holes, and discuss their origin. Also, we compare the H\textsc{i} holes to the distribution of the high-velocity gas and explore probable links between them.

In chapter 5 we present the case of NGC 253. We present the H\textsc{i} data and compare these results with those of studies at other wavelengths. We discuss some possible explanations for the extra-planar H\textsc{i} which has been found more than 10 kpc above the disk. We describe a schematic model, which seems to fit the multi-wavelength data, where the H\textsc{i} forms a shell around the super bubbles of hot gas.

Finally, we compare our findings with observations of other galaxies where extra-planar H\textsc{i} and high-velocity gas have also been found.