High-velocity gas in NGC 6946

ABSTRACT — In this chapter we analyse the high-velocity H\textsuperscript{i} in NGC 6946. We find $2.9 \times 10^8 \, M_\odot$ of H\textsuperscript{i} showing velocities deviating more than 50 km s\textsuperscript{-1} from local galactic rotation. This is 4\% of the total H\textsuperscript{i} mass. Many of these features can be associated with regions of massive-star formation. In addition, we find that part of the high-velocity H\textsuperscript{i} is in a lagging halo, covering the entire inner disk. The association of high-velocity H\textsuperscript{i} with star formation on small and large scales suggests that the gas has been accelerated in a Galactic Fountain. The presence of high-velocity H\textsuperscript{i} at large galactic radii on the other hand, indicates that part of the anomalous H\textsuperscript{i} in NGC 6946 needs a different explanation. For these complexes, accretion is a likely mechanism.

3.1 Introduction

Previous work has shown that several spiral galaxies have gas in their halos. Deep H\textsuperscript{i} observations of the edge-on spiral NGC 891, a galaxy considered to be similar to the Milky Way, have revealed H\textsuperscript{i} reaching up to several kpc into the halo (Swaters et al. 1997; Fraternali et al. 2004b; Oosterloo et al. 2006). Detailed modelling of the kinematics shows that this H\textsuperscript{i} rotates more slowly than the H\textsuperscript{i} in the disk (Swaters et al. 1997; Fraternali et al. 2005). Fraternali et al. also show that the rotational velocity of the H\textsuperscript{i} decreases with increasing distance from the plane. The extra-planar H\textsuperscript{i} is seen on both sides of the plane and associated with the bright optical disk, where there is massive-star formation (as traced by the H\alpha). This is very suggestive of a connection between the two phenomena (Van der Hulst 1996).

In the less inclined spiral galaxy NGC 2403 (Schaap et al. 2000; Fraternali et al. 2001), a similar slowly rotating H\textsuperscript{i} halo has been observed. This H\textsuperscript{i} halo is seen projected onto the bright optical disk. In addition to the slower rotation, a radial inflow of 20 km s\textsuperscript{-1} has been found.
Similar H\textsc{i} halos are also seen around other galaxies such as the super-thin galaxy UGC 7321 (Matthews & Wood 2003) and the galaxy NGC 4559 (Barbieri et al. 2005). This increasing number of detected H\textsc{i} halos in different types of galaxies suggests that slowly rotating extra-planar H\textsc{i} is, perhaps, a common phenomenon in spiral galaxies.

Our own Galaxy also has complexes of H\textsc{i} that do not follow the differential galactic rotation. These are the Intermediate (IVC) and High (HVC) Velocity Clouds. Their distances and, therefore, their masses are uncertain. The few HVC complexes for which distances are known are \(\sim 10\) kpc (Wakker 2005). Some, more disk related H\textsc{i} structures in the Milky Way are known to reach distances up to \(2\) kpc from the plane (Lockman & Piopryhora 2005).

Various mechanisms have been suggested for the origin of the extra-planar H\textsc{i} and the high-velocity gas. One of these is the so called Galactic Fountain (Shapiro & Field 1976; Bregman 1980) according to which supernovae explosions and stellar winds are the driving forces that accelerate the gas to high velocities. This gas, heated by the stars and supernovae, may leave the disk via chimneys, elongated H\textsc{i} shells in the vertical direction that have broken out of the disk. Eventually, this gas will cool and fall back onto the disk.

Besides the galactic fountain, other explanations have been proposed. The high-velocity gas may have fallen in from outside: it may have been accreted from a small, tidally disrupted companion galaxy, or it may have been tidally removed from the galaxy itself and fallen back later. Alternatively, the gas may be primordial, falling in from outside (as proposed originally by Oort 1970, for the HVCs).

Previous studies of edge-on and inclined galaxies have provided information on the vertical extent of the extra-planar H\textsc{i} and its rotation. The vertical velocities of the H\textsc{i}, however, can only be measured directly in face-on galaxies. Furthermore, in the latter it is possible to see the anomalous H\textsc{i} in projection on the disk, so that it is possible to associate the H\textsc{i} complexes with structures in the disk.

We have, therefore, observed the nearby spiral galaxy NGC 6946, which is almost face-on. Observations by Kamphuis & Sancisi (1993) of NGC 6946 have revealed the presence of widespread high-velocity H\textsc{i}. They observed the high-velocity gas predominantly in the direction of the bright optical disk and near holes in the H\textsc{i} distribution (Kamphuis 1993). Because of this, they suggest a link with the stellar winds and supernovae (i.e. a galactic fountain). Their data were, however, not sensitive enough to detect individual complexes and had to be smoothed to improve the signal-to-noise. Consequently, a detailed analysis of the widespread high-velocity gas and a study of its correlation with other phenomena could not be made. A detailed picture of the spatial distribution of this gas is clearly necessary for understanding the origin of this component.

As we showed in the previous chapter, the new H\textsc{i} observations of NGC 6946 have sufficient sensitivity and resolution to resolve distinct high-velocity H\textsc{i} features. In this chapter, we separate the high-velocity gas from the rotating H\textsc{i}, and search for possible correlations with features and phenomena in the disk.
3.2 Analysis

The \( xv \) diagrams presented in the previous chapter (Fig. 10) indicate that the \( \text{H}_\text{I} \) spectra often have asymmetric wings. The high-level contours appear symmetric, whereas the low-level contours show a lot of irregular structures, mainly towards the lower rotational velocities. Line-profiles in the direction of \( \text{H} \) holes are often even more disturbed, showing two or more peaks and broad wings. This is the anomalous gas, which we will discuss in this chapter.

3.2.1 Derotation

In order to study the anomalous velocity gas component, we have to separate it from the regularly rotating \( \text{H}_\text{I} \) disk. We do this by defining the \( \text{H}_\text{I} \) that differs more than 50 km s\(^{-1}\) from local differential galactic rotation as anomalous \( \text{H}_\text{I} \) or ‘high-velocity’ \( \text{H}_\text{I} \). For each position we need to know the velocity of the disk in order to derive the deviating velocity \( V_{\text{dev}} \). For this we used the velocity field derived in

\[ V_{\text{dev}} = V_{\text{obs}} - V_{\text{sys}} \]
the previous chapter. For the construction of the velocity field (see Sect. 2.3.3) we used Gaussian fitting of the profiles. At positions where this fit failed, the velocities were interpolated from the surrounding positions. Each profile in the data cube was then shifted by its radial velocity (as represented in the velocity field). This removes the systematic motion and results in a data cube where the 3rd axis is $V_{\text{dev}}$. This is illustrated in Fig. 3.1.

The data on the approaching, eastern side of NGC 6946 are severely affected by the Galactic foreground emission. On the receding, western side this problem does not arise. There we can unambiguously study the anomalous H\textsc{i}.

Use of the observed velocity field (white dots in the top panel) instead of a model takes care of most of the local, small, non-circular motions present in the disk. These deviations from circular rotation are visible in the top panel of Fig. 3.1 as wiggles. These wiggles (see also the velocity field in Chapter 2) have, therefore, disappeared in the bottom panel.

After removal of the rotation, the $x\theta$ diagram (Fig. 3.1, bottom) shows the regularly rotating gas at $V_{\text{dev}} = 0$ and makes the anomalous H\textsc{i} clearly visible at $|V_{\text{dev}}| \geq 50$ km s$^{-1}$. In the derotated cube (Fig. 3.2, and 3.3 at 64" resolution), each channel shows H\textsc{i} at a given $V_{\text{dev}}$. The central channels contain the dominating emission of the cold disk. They appear therefore very similar to the total H\textsc{i} map (Fig. 6).

The top and bottom channels in Fig. 3.2 show that a significant amount of H\textsc{i} is present with $|V_{\text{dev}}|$ larger than 50 km s$^{-1}$. Since the H\textsc{i} velocity dispersion in a disk galaxy is normally around 10 km s$^{-1}$ (see also Fig. 17), these cannot be the wings of the Gaussian velocity distribution of the gas in the disk.

### 3.2.2 Large-scale distribution and kinematics

It is clear from Figs. 3.2 and 3.3 that most of the H\textsc{i} with $|V_{\text{dev}}| > 50$ km s$^{-1}$ is seen in the direction of the bright optical disk (as a reference, the outline of the bright optical disk at $R_{25}$ has been plotted). On one side (in velocity), the high-velocity H\textsc{i} seems to form a spiral pattern (best seen in channel +50 km s$^{-1}$ in Fig 3.2). Some of these spiral arms coincide with the optical arms, others are projected on an interarm region. We will discuss this further in Section 3.3.1.

High-velocity H\textsc{i} is also seen outside $R_{25}$. This is most obvious in the 64" data (Fig. 3.3). Two obvious regions are the west part of NGC 6946 at the negative-velocity side, where gas in the north-west connects to a faint plume of gas and the northern part of NGC 6946 at the positive-velocity side, where there is gas with anomalous velocities in between the outer spiral arm and the main disk.

The high-velocity emission is not distributed symmetrically with respect to the centre of NGC 6946. The gas with negative $V_{\text{dev}}$ is more extended to the south-west, while the gas with positive velocities shows the opposite. In an $x\theta$ diagram of the original data this anomalous gas is thus seen mainly on the lower rotational side of the cold disk emission as a beard (Sancisi 2001). This effect can also be seen in $x\theta$ space in Fig. 3.21, later in this chapter. This is similar to what is seen in the more inclined galaxies NGC 2403 and NGC 891. The beard has been interpreted as a lagging halo. There is, however, also an important difference: in NGC 6946, emission is also seen at the high rotational velocity side, as, for example, the spur in Fig. 3.1 at
Figure 3.2– Channel images of the 22" resolution data after derotation. The channel separation and width are 12.6 km s\(^{-1}\). In the top-left corner of each panel, the velocity relative to the disk rotation is shown. Contours are at $-1.5$, $-0.75$, $0.75$ (1.5$\sigma$), $1.5$, $3$, $6$, $12$, and $24$ mJy beam\(^{-1}\). The grey line shows the kinematic minor axis. The ellipse outlines the region inside $R_{25}$. The beam size is indicated in the bottom-left corner. The empty regions on the eastern side are due to the masking out of the Galactic foreground emission.
Figure 3.3— Channel images at 64″ resolution after derotation. The channel separation and width are 12.6 km s$^{-1}$. In the top-left corner of each panel, the velocity relative to the disk rotation is shown. Contours are at $-2.56, -1.28, 1.28 (1.5\sigma), 2.56, 5.12, 10.2, 20.4,$ and $40.8$ mJy beam$^{-1}$. The grey line shows the kinematic minor axis. The ellipse outlines the region inside $R_{25}$. The beam size is indicated in the bottom-left corner. The empty regions are due to masking out of the Galactic foreground emission.
Figure 3.4– Total H\textsc{i} map showing the cuts parallel to the major and the minor axis corresponding to the position-velocity diagrams in Figs. 3.5 and 3.6.

2\arcmin from the centre. The velocities of these complexes cannot be explained as rotation. Also, there is H\textsc{i} at forbidden velocities as shown in Fig. 3.7.

The H\textsc{i} at velocities closer to systemic than the bulk of the disk is identified as beard gas. The H\textsc{i} at the other side of the disk (in velocity space), further away from $V_{\text{sys}}$, we call the quiff. Finally, there is also gas (the so called forbidden gas) in the forbidden quadrants of the $xv$ diagram and apparently counter rotating (cf. Fig. 3.7). The anomalous H\textsc{i} in these different regimes is likely to represent different gas components.

We have constructed separate maps of the H\textsc{i} with $|V_{\text{dev}}| > 50$ km s$^{-1}$ on the beard and the quiff side (Fig. 3.8). We have divided the disk in an approaching and a receding side, using the 43 km s$^{-1}$ ($V_{\text{sys}}$) isovelocity line from the corresponding velocity fields (shown as the black-and-white line), because beard and quiff switch
Figure 3.5— Position-velocity diagrams parallel to the minor axis (see Fig. 3.4). The slice separation is 2.5′. In the top-left corner of each panel, the distance to the minor axis is shown in arcminutes. Contours are at \(-0.9, -0.45, 0.45 (1.5\sigma), 0.9, 1.8, 3.6, 7.2,\) and \(14.4 \text{ mJy beam}^{-1}\). The white regions are due to the masking out of the Galactic foreground emission. The spatial and velocity resolutions are indicated in the bottom-left corner.
Figure 3.6– Position-velocity diagrams parallel to the major axis (see Fig. 3.4). The slice separation is 2.5′. In the top-left corner of each panel, the distance to the major axis is shown in arcminutes. Contours are at $-0.9$, $-0.45$, 0.45 (1.5σ), 0.9, 1.8, 3.6, 7.2, and 14.4 mJy beam$^{-1}$. The white regions are due to the masking out of the Galactic foreground emission. The spatial and velocity resolutions are indicated in the bottom-left corner.
sides in velocity-space when switching from the approaching to the receding side of the galaxy. The four images in Fig. 3.8 all appear discontinuous around the systemic velocity. This reflects the difficulty of detecting the high-velocity gas around this velocity because of confusion with Galactic foreground emission.

Clearly, there is more H\textsc{i} on the beard than on the quiff side: at 64'' the total mass of the beard gas is $2.4 \times 10^8 M_\odot$ compared to $0.5 \times 10^8 M_\odot$ of H\textsc{i} on the quiff side. Sources of deviating velocities such as vertical outflows and infall of gas are expected to occur equally on both sides of the disk. In velocity space this gas would be seen equally spread over the beard side as the quiff side. A lagging halo, on the other hand, is only seen as beard. Therefore, the quiff can probably be unambiguously interpreted as gas moving vertically, while the beard is a mixture of several kinematical gas components. The strong asymmetry between beard and quiff is a strong indication for the presence of a lagging halo in NGC 6946.

The quiff is almost exclusively seen projected on the bright optical disk, which suggests a link to stellar activity. On smaller scales, there seems to be an anti-correlation between regions with quiff and regions with beard H\textsc{i}. The most striking example of this is the maximum in the quiff map at 22''. An $xv$ diagram of this region is shown in Fig. 3.23, top panel (see also Fig. 3.12). In terms of vertical flows, this would mean that those flows are mainly one-sided. At 64'' this anti-correlation is less apparent.

The beard is very extended. It covers the complete inner disk and large parts of the eastern outer disk. On the west side it is concentrated in a few distinct complexes, of which the two most striking have been labelled the western ("W") and south-western ("SW") complex.

The beard map also contains the forbidden gas, since it is on the same side in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure3_7.png}
\caption{The definitions for the several anomalous H\textsc{i} regimes as we use them in this chapter.}
\end{figure}
Figure 3.8— The left panels show the beard+forbidden gas, the right panels show the quiff. The top panels are at 64″ resolution, the bottom at 22″ resolution. The beam sizes are indicated in the lower left corner of each panel. The black-white line marks the division between the approaching and the receding sides (see text). The ellipses outline the bright optical disk ($D_{25}$).

velocity space (see Fig. 3.7. This forbidden H I is shown in Fig. 3.9. All forbidden gas complexes are part of larger complexes with beard velocities. The velocity extent of these has to be very high to reach the forbidden velocity range, especially near the major axis. The total mass of this gas is $0.5 \times 10^8 M_\odot$, which is about the same as the H I mass of the quiff. The distribution of the forbidden gas is, however, completely different.

The largest forbidden complex is seen just east of the centre and is 20 kpc in extent. At higher resolutions (Fig. 3.10, middle and left panel), it appears as separate regions, but at low resolution it is not clear whether this is actually one continuous object or a blend of smaller complexes with possibly different origins. As we will show in Fig. 3.22 (bottom panels), part of it is clearly associated with star forming re-
regions and the H\textsubscript{I} holes in the disk. Unfortunately, the study of the kinematics of the disk and of the anomalous H\textsubscript{I} of the north-eastern outer disk suffers from confusion with the Galactic Foreground emission.

The forbidden gas just west of the centre is more compact. It is seen projected on a few large H\textsubscript{I} holes and regions of massive-star formation (see also Fig. 3.22, top panels). Here, the gas seems clearly associated with phenomena in the disk. Figure 3.11 shows a $xy$ diagram of the complex. The structure of the anomalous H\textsubscript{I} is best seen in the 13" resolution data (greyscale+contours), while the full extent of the forbidden complex is clear at 64" resolution (contours). The H\textsubscript{I} at the location of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.9.png}
\caption{Contours of the forbidden H\textsubscript{I} in NGC 6946 at 64" resolution plotted on top of the total H\textsubscript{I} distribution at 13" resolution. The levels shown are 16.8, 33.6, 67.2, and 134.4 mJy beam\textsuperscript{-1}km s\textsuperscript{-1}. The lines show the locations of the slices in Figs. 3.10 (north-south) and 3.11 (east-west). The forbidden emission has not been corrected for the primary beam attenuation.}
\end{figure}
Figure 3.10— Position-velocity diagrams of the forbidden complex on the north-eastern side of the disk at the resolutions: 13\arcsec (left), 22\arcsec (middle), and 64\arcsec (right). The orientation of the slice is shown in Fig. 3.9 by the vertical line. North (N) is left, South (S) is right. The contours in each panel are at $-3\sigma$, $-1.5\sigma$, $1.5\sigma$, $3\sigma$, $6\sigma$, $12\sigma$, $24\sigma$, $48\sigma$, and $96\sigma$. The white regions are due to the masking of the Galactic Foreground Emission. The horizontal line represents $V_{\text{sys}}$. The spatial and velocity resolutions in each panel are shown in the bottom right-hand corner.

the hole (at +3\arcsec) seems part of a broken shell, suggesting vertical motions. But the anomalous HI is also extending to smaller galactic radii, forming a beard. Probably the forbidden velocities are a sign for vertical motions, similar to the quiff, but with some rotational contribution.

3.2.3 Spurs and clouds

The individual anomalous HI features, seen spread over the disk (Figs 3.5 and 3.6), seem to be sometimes one-sided, sometimes two-sided in $x\nu$ space. The majority is seen in the direction of the bright optical disk (Fig. 3.8, bottom panels). Roughly, they can be divided in shells, spurs, and clouds. Their appearance often depends strongly on the orientation of the $x\nu$ slice. The edge of a shell, for example, can have the same appearance as a spur. Also angular resolution may have a strong effect. Most spurs show up most clearly in the 22\arcsec data. This suggest that the spurs have a typical angular scale of $\sim 20\arcsec$ or 0.6 kpc. Masses are typically of the order of $10^5$–$10^6 M_\odot$.

A striking example of a spur is the feature on the quiff side in Fig. 3.12 (middle panel). The gas reaches velocities of more than 100 km s$^{-1}$ in excess of the local disk velocity. A similar spur is seen on the other side near the centre of the panel.

Some anomalous HI features appear as cloud-like complexes, such as the those shown in Fig 3.13 (see arrows in middle panel). The cloud on the approaching side shows a velocity deviating about 210 km s$^{-1}$ with respect to local galactic rotation. The low resolution data (right panel) shows that this cloud is connected to the disk at that location.

For one anomalous HI feature we have an age estimate. A large cloud (Fig. 3.14) is seen in the direction of an HI hole (hole 108, Chapter 4, Fig. 4.2), but in $x\nu$ space it seems to be connected to the large hole fr. 96. The skewed appearance of the hole
and the location of the cloud suggest that this gas may have moved 2 kpc away in projection on the sky. The line-of-sight velocity of the cloud with respect to the hole is ~70 km s$^{-1}$. The time for the cloud to move 2 kpc projected on the sky is of the order of a few $10^7$ yr. This is similar to the rough age estimate for this hole, suggesting that this high-velocity H\textsc{i} cloud may indeed have originated from the hole.

### 3.2.4 Widespread high-velocity gas

There is a dramatic change in appearance of the anomalous H\textsc{i} between the different resolutions. At 64$''$ the high-velocity emission appears much more extended and massive than at high resolution (Fig. 3.8). This is also apparent in $xv$ diagrams, such as Figs. 3.10, 3.12, and 3.13. H\textsc{i} complexes that appear as distinct clouds in $xv$ space at high resolution (Fig. 3.13, left and middle panel), are blended or connected by low level emission at low resolution (right panel). Separate spurs seem to form a smooth, widespread layer of anomalous H\textsc{i}, both at the quiff side as the beard side (Fig. 3.12).

Naturally, lower resolution causes blending of the small-scale structures. However, the detected mass of the anomalous H\textsc{i} at 64$''$ resolution is much larger than that at 22$''$ resolution. We detect $2.9 \times 10^8 M_\odot$ of H\textsc{i} with $|V_{\text{dev}}| > 50$ km s$^{-1}$ at 64$''$ versus $1.2 \times 10^8 M_\odot$ at 22$''$. This large difference is a strong hint that a large fraction of the high-velocity H\textsc{i} is diffuse (on a few 100 pc scale). At high resolution, we probably observe only ‘the tip of the iceberg’.

As discussed earlier, the quiff and the beard probably contain different components of anomalous H\textsc{i}. This difference may also be reflected in the fraction of diffuse H\textsc{i} in both beard and quiff. To test this, we compared the flux-ratio of the beard at 22$''$ and 64$''$ with that of the quiff at those resolutions. For the beard H\textsc{i} this is about...
2.4, while for the quiff this ratio is only 1.7. Thus the beard has a larger fraction of the diffuse H\textsc{i}.

3.2.5 Anomalous H\textsc{i} at large radii

As mentioned before, two anomalous complexes are seen at large galactic radii on the western side of the disk. We denote them as the western and the south-western high-velocity H\textsc{i} complexes (‘W’ and ‘SW’ in the left panels of Figs. 3.8 and 3.15).

The western complex measures about 4 by 7 kpc in size and shows a velocity extent of about 80 km s\(^{-1}\) (Fig. 3.15, right panel). In this \(xv\) diagram, it seems to be connected to the north-western plume (Fig. 3.15, left panel). The plume extends about 28 kpc to the north-west; it starts at the local disk velocity and shows almost no velocity gradient. This continuous velocity structure of the western complex and the plume suggest that they form one gas complex. The combined mass is \(0.8 \times 10^8 M_\odot\). This is approximately the H\textsc{i} mass of a small galaxy. For comparison, the two...
companions (Fig 20) of NGC 6946 have masses of $0.9 \times 10^8 \, M_\odot$ and $1.2 \times 10^8 \, M_\odot$.

In the direction of the plume and the complex no stars are seen (Fig. 4). Stellar winds and supernovae are, therefore, unlikely to be the source of the gas motions. It is more likely that the H\textsc{i} is the result of an interaction or an accretion. As already mentioned in the previous chapter (Section 2.4), the plume is at the same side of NGC 6946 as the two companions. Follow-up observations with the WSRT show no H\textsc{i} between the plume and the companion galaxies. The mass of the complex suggests that it might have been part of a third companion. Since we see no stellar counterpart, this is likely an intergalactic H\textsc{i} complex which contains no stars. Alternatively, the plume is originating from the H\textsc{i} disk of NGC 6946, pulled out from the galaxy by tidal interaction, which would explain the similarity in velocity with the disk of NGC 6946.

On the south-western side of the disk there is H\textsc{i} emission at velocities from 120 km s$^{-1}$ (=disk velocity) down to about 20 km s$^{-1}$ (Fig. 3.16). It is about 7 by 10 kpc in extent and contains approximately $0.6 \times 10^8 \, M_\odot$. At the location of this high-velocity complex, the disk of NGC 6946 shows no peculiar structures, except for a H\textsc{i} hole much smaller in size than the complex. The absence of stars may also for this region be an indication that this is the result of an accretion. There is, however, no large scale disturbance in the disk of NGC 6946 to support this possibility.

It is striking that all accretion candidates are seen on the beard side in velocity space. The number of cases is, however, too small for statistic purposes. If, however, the clouds fall from random directions onto a rotating disk at various velocities (with a average angular momentum of 0), the chances are bigger that they appear in $xv$ space on the beard/forbidden side than on the quiff side. A larger beard than a quiff would, therefore, be expected.
Figure 3.15— The north-western plume and its velocity structure. On the left the high resolution (greyscale) and the low resolution (contours) H I distributions are shown. Contours are given for 1.25, 2.5, 5, 10, and $20 \times 10^{19}$ cm$^{-2}$. The higher contours have been omitted. The line indicates the position of the $xy$ diagram on the right panel. Contours in this plot are at $-1.3$, $0.65$, $0.65$ (1.5σ), 1.3, 2.6, 5.2, and 10.4 mJy beam$^{-1}$. In both panels the resolution is indicated in the bottom left corner.

3.2.6 Gas in interarm regions

Not all motions in the disk of NGC 6946 that deviate from pure rotation are necessarily vertical flows or lagging rotation in the halo. Although the predominant motion in the disk of NGC 6946 is rotation, there are also deviations which show up as wiggles in the velocity field and follow the spiral arms (Fig. 3.17). These may be due to `streaming motions’ and may be related to the mass contrast between arms and interarm regions.

The largest wiggles are seen in the direction of the interarm regions. The velocity field in Fig. 3.17 is constructed from the velocity-weighted mean of the H I (first moment) to be able to assign a velocity also to the interarm gas, which does not have a Gaussian velocity distribution. The amplitude of the wiggle in the northern interarm is up to 100 km s$^{-1}$. If this were in the plane of the disk, it would be 160 km s$^{-1}$! This much higher than expected for density waves. Furthermore, the gas in this interarm region has a very high dispersion (Fig. 3.18, bottom left panel), which is not expected.
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Figure 3.16– Position-velocity diagrams showing the south-western high-velocity HI complex at 64″ resolution. Contours are at −1.3, −0.65, 0.65 (1.5σ), 1.3 , 2.6, 5.2, 10, 21, 41 and 83 mJy beam⁻¹. The locations of the slices are indicated by the straight lines in the upper panel, where the greyscale shows the total HI at 64″ resolution. Overplotted in white contours is the beard gas at 42, 84, 168, and 336 mJy beam⁻¹ km s⁻¹.

for simple streaming motions. A similar case of such high non-circular motions reported for another galaxy is the ‘high-velocity through’ in the eastern part of M 81 (Yun, Ho & Lo 1994), which is thought to be the location where M 82 passed through the H I disk of M 81.

The gas in the southern interarm region shows a more regular behaviour (Fig 3.18, top panel). Its average line-of-side velocity deviation is about 30 km s⁻¹. However, in a small region, the velocity structure seems discontinuous (Fig. 3.17 and Fig. 3.18, bottom right panel). Part of the H I, about 1 kpc wide, is seen blue-shifted by about 40 km s⁻¹.
3.3 Discussion

3.3.1 Anomalous H I and star formation

Both the anomalous H I on the beard side and the H I on the quiff side are seen concentrated in the direction of the bright optical disk (Fig. 3.8). It is striking that at 22") the high-velocity H I features form a sharp transition at the edge of the bright optical disk (except for the northern arm and interarm region). Bright H II regions (Fig. 3.19, bottom left panel) appear confined to the same region. This correspondence suggests a connection between the high-velocity H I and the Hα component.

Figures 3.20 and 3.21 show the velocity distribution of the derotated H I emission after integrating along the major and the minor axis respectively. They illustrate the overall spatial-velocity structure of the H I after derotation. Also shown are integrations of the Hα (Data from Ferguson, Gallagher & Wyse 1998) in the same directions (black line at the bottom of Figs. 3.20 and 3.21). Especially for the H I emission at negative $V_{\text{dev}}$ in Fig. 3.20, the velocity width seems to correlate with the peaks in the Hα
Figure 3.18— Position-velocity diagrams showing the wiggles in the interarm regions as seen in Fig. 3.17. The top panel shows a north-south cut including the northern and southern interarm regions. The bottom panels show $xv$ diagrams of cuts taken at the locations as shown in Fig. 3.17 and indicated with the vertical lines in the top panel. The contours in each panel are at $0.66$, $0.33$, $0.33(1.5\sigma)$, $0.66$, $1.32$, $2.46$, $5.28$, $10.6$, and $21.2$ mJy beam$^{-1}$. The crosses show the resolutions in both velocity and position. The bottom panels are on the same scale.

brightness. Outside the bright optical disk (marked by the dashed lines in Figs. 3.20 and 3.21), the H I spectra are less wide, and only little H $\alpha$ emission is present.

The high-velocity H I in Fig. 3.21 shows an asymmetry: H I with positive deviating velocities is more concentrated towards the north-east, while the H I with negative $V_{dev}$ is mainly seen on the south-west side. This skewness is explained by the lagging of the halo rotation. Figure 3.21 shows that the lagging halo is mainly confined to the direction of massive-star formation.

On small scales, however, it is often difficult to connect distinct high-velocity features, such as spurs, to local stellar phenomena, because the H I data resolution is almost 20 times larger than that of the optical images. Despite that, Fig. 3.22 shows two examples where the connection between high-velocity H I and star forming re-
regions can be seen. The H\textsc{i} profiles in the top-right panel are much broader, both at the high and low velocity-side, in the direction of the H\textsc{ii} complexes (top-left panel) and blue stellar clusters. In the context of the galactic fountain, these anomalous velocities would be interpreted as the gas being vertically accelerated by the stellar winds and supernova explosions. This spiral arm also harbours a few H\textsc{i} holes, from which the anomalous gas may be originating.

The velocity structure of the H\textsc{i} in the bottom example in Fig. 3.22 is more complicated. The H\textsc{i} emission from this spiral arm is in the same range as the Galactic Foreground Emission (white region in the bottom-right panel of Fig. 3.22). Fortu-
nately this affects only a small velocity range. In this spiral arm, the anomalous H\textsc{i} has mainly positive $V_{\text{dev}}$, up to 230 km s$^{-1}$. Part of this high-velocity gas is therefore marked as forbidden and cannot be part of a lagging halo. One possibility is that this gas is blown out on the back side of the disk of NGC 6946 by stellar winds and supernovae. The spiral arm is very bright in blue (see Fig. 3), indicating the presence of many young stellar clusters (which are generally associated with a large number of SNe). Furthermore, a few clear H\textsc{i} holes have been detected (see Chapter 4), bordered by bright H\textsc{ii} complexes (Fig. 3.22, bottom-left panel). If, however, this high-velocity gas is part of the the large western forbidden complex (see Fig. 3.9), then it is probably unrelated to the massive-star formation.

Spurs also occur in regions where no star formation is apparent, both in the inner as in the outer disk. This is illustrated in Fig. 3.23. The most prominent quiff feature in NGC 6946 (top panel, $2 \times 10^5 M_\odot$), which we showed earlier (e.g. Fig. 3.1), is seen in projection against a region with relatively low stellar activity. The H\textsc{i} disk also shows no clear distortion except for a few small H\textsc{i} holes. Perhaps, we are witnessing H\textsc{i} that has fallen back from the halo.

**Figure 3.20** – A total H\textsc{i} $xv$ diagram for NGC 6946 parallel to the minor axis after strip integration of the derotated H\textsc{i} emission along the major axis. The bottom profile shows the H\textalpha emission also integrated along the major axis. The dashed lines indicate the $D_{25}$ of NGC 6946.
3.3.2 Accretion

As shown in Chapter 2, there are several indications that NGC 6946 has undergone some minor interactions in the recent past: the disk seems mildly warped and slightly lopsided; one spiral arm is amplified and has a peculiar, high velocity gradient; the kinematics of the outer disk appears disturbed; the disk shows a sharp edge on the south-western side; there is a high level of star formation.

NGC 6946 has no large companion and the two companions on the west appear undisturbed. We do observe a plume of H\textsc{i} at the edge which may be gas being accreted or pulled out of the disk. Other possible accretion related complexes are the south-western anomalous complex and the extended complex with gas at forbidden velocities east of the centre of NGC 6946 (Fig. 3.9). If these complexes are all being accreted, then it is remarkable that we do not observe any H\textsc{i} clouds outside the disk of NGC 6946. Perhaps, the complexes were part of a single low-luminosity satellite that has been tidally disrupted by NGC 6946.

3.3.3 3D picture

It seems that part of the anomalous H\textsc{i} is connected to star formation, and part to accretion. How do the results for NGC 6946 compare with those obtained for the more inclined galaxies NGC 891 and NGC 2403? Do we observe the same phenomena as
in those galaxies?

For both NGC 891 and NGC 2403, modelling shows that the anomalous H I is extra-planar and rotates more slowly than the cold disk. In the edge-on galaxy NGC 891 it is possible to measure the extent of the halo gas. In the less inclined galaxy NGC 2403 the modelling and sensitive observations have revealed a radial inflow.

NGC 6946 is not exactly face-on, but has an inclination of 38°, so we can measure the rotation of the gas. We find a lagging halo with similar large-scale kinematics as NGC 2403. Also the amount of anomalous H I is about the same as in the other galaxies NGC 891 and NGC 2403. The anomalous fraction in NGC 891 has been estimated to be about 10% of the total H I mass (Swaters et al. 1997). Fraternali et al. (2001) find a similar mass fraction in NGC 2403. In NGC 6946 we measure about 4% of H I with $|V_{\text{dev}}| > 50\text{ km s}^{-1}$, and there are indications that it may be as much as

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**Figure 3.22**— High-velocity H I seen in the direction of star forming regions. The left panels show the H a from (Ferguson, Gallagher & Wyse 1998) in greyscale, and the anomalous H I in contours. Levels are at 0.005, 0.010, 0.015, 0.020, 0.025, 0.030, and 0.035 mJy beam$^{-1}$. The resolution of the H I is shown in the bottom left corner. The right panels show the corresponding $x v$ diagrams. The positions and the scales are shown on the left panels by the lines and tick marks. The contours are at $-0.57$, $-0.29$, $0.29 (1.5\sigma)$, $0.57$, $1.1$, $2.3$, $4.6$, $9.1$, and $18.2$ mJy beam$^{-1}$. The resolution is shown in the bottom-right corner.
DISCUSSION

Figure 3.23– High-velocity H\textsubscript{I} seen in the direction of regions with little star formation. Contours and lines are the same as in Fig 3.22.

18\%, when including all the H\textsubscript{I} that does not follow the disk rotation. From this we can conclude that we, indeed, observe the same phenomenon as in NGC 891 and NGC 2403.

What NGC 6946 adds to the 3D picture is:

- Vertical motions have been found that are associated with star forming regions. These may be the streams that have brought part of the H\textsubscript{I} in the halo. It also shows that the gas in the blow out stage of this Galactic Fountain (e.g. Shapiro & Field 1976) is not necessarily hot, but may be still, partly, in its neutral state.

- Part of the anomalous H\textsubscript{I} is clearly not associated with stellar activity (this is also seen in NGC 891 and NGC 2403). For this part, accretion seems a more likely explanation.

- The gas accretion in NGC 6946 may be analogous to the stellar streams observed in M31 (Ibata et al. 2001b; Ferguson et al. 2002) and the Milky Way (Ibata, Gilmore & Irwin 1994; Johnston, Spergel & Hernquist 1995; Ibata et al. 2001). It may also help explaining the unusually high rate of star formation taking place in the relatively isolated NGC 6946.
3.4 Conclusions

We confirm the presence of widespread high-velocity gas in NGC 6946. The total amount of gas with $|V_{\text{dev}}| > 50 \text{ km s}^{-1}$ is $2.9 \times 10^8 M_\odot$, which is 4% of the total $\text{H} \text{I}$ mass. This is comparable to the values found for NGC 2403 and NGC 891 (Swaters et al. 1997; Fraternali et al. 2001, 2004b) and for the starburst galaxy NGC 253 (Chapter 5).

Some of the high-velocity features in NGC 6946 are interpreted as vertical flows of gas, either blown out of the disk by stellar activity, or falling (back) on the disk. The $\text{H} \text{I}$ in the halo of NGC 6946 is rotating more slowly than the cold disk. Its mass is probably about half of the total anomalous $\text{H} \text{I}$. This halo is similar to the lagging halos observed in NGC 891 and NGC 2403.

The distribution of the anomalous $\text{H} \text{I}$ seen mainly in the direction of the bright optical disk and some clear associations of high gas velocities with star forming regions suggest that the Galactic Fountain is an important mechanism in driving the anomalous $\text{H} \text{I}$.

We have evidence for ongoing accretion, mainly in the outskirts of the $\text{H} \text{I}$ disk.