Summary and conclusions

1. Introduction

For almost three decades neutral hydrogen moving at velocities unexplainable by galactic rotation has been observed. These so-called high-velocity clouds (HVCs) have been invoked as evidence for infall of neutral gas to the galaxy, as manifestations of a galactic fountain, as energy source for the formation of supershells, etc. No general consensus about their origin has presently been reached. However, it is becoming clear that no single model will suffice to explain all HVCs. A better understanding is mainly hampered by the fact that the distance to individual clouds remains unknown. An overview of the current status of the distance problem is given in Chapter 12.

Recently, the whole sky has been surveyed for high-velocity gas (Bajaja et al. 1985, Hulsbosch & Wakker 1988, Chapter 2). Older surveys, notably the one by Giovanelli (1980), provided much insight into the phenomenon but suffered from incompleteness. In the new surveys (having 35′ beams) the whole sky north of declination −18° is covered with a 1°×1° grid and a detection limit of 0.05 K (corresponding to about $10^{18}$ atoms/cm$^2$), while south of −10° the grid is 2°×2° with detection limit 0.08 K. All profile components with $|v_{lsr}| > 90$ km s$^{-1}$ were selected. In Chapters 3 and 4 an analysis of these data is presented, including the first homogeneous catalogue of HVCs. There are two types of HVCs: those with $|v_{lsr}| < 200$ km s$^{-1}$ and those with larger velocities, which are also called VHVCs. Section 2 highlights a few of the results.

Detailed maps of the structure of HVCs have been made since 1973 (Giovanelli, Cram & Verschuur). Much angular and velocity fine structure was found. The smallest concentrations were unresolved with the 9′ to 20′ beams used. Giovanelli & Haynes (1976) discovered that at this resolution the velocity profile often showed a sharp (FWHM 7 km s$^{-1}$) peak on top of a broader (FWHM 23 km s$^{-1}$) plateau. The narrower profiles were only observed in the brighter parts of the clouds. From 1979 onward, data at 1′ resolution have been taken with the Westerbork synthesis telescope, which show that the intrinsic linewidths are narrower (FWHM 3–6 km s$^{-1}$) and that a large part of the broadening of the profiles can be attributed to beam smearing. Some of these maps are discussed in Chapters 6 and 8. A summary of the results is given in Sect. 3.
To understand and explain the different aspects of the data, especially the $l-b-v_{1r}$ distribution of the clouds in the catalogue, model calculations were conducted. In these models the orbits of an ensemble of clouds in the potential of the Galaxy are followed. Sect. 4 summarizes the results.

In Sect. 5 we draw some overall conclusions from the research reported in this thesis and outline some outstanding problems.

2. Survey results

2.1. Sky distribution

The latitude distribution of the flux from high-velocity gas shows that it is not limited to high galactic latitudes, as was previously thought, but that there is a concentration toward low galactic latitudes. Further, negative velocities are not as predominant as was apparent from the first surveys for high-velocity gas. This impression was created by the lower sensitivity of the early surveys and the fact that most of the, generally fainter, positive-velocity clouds are in the southern sky. However, it remains true that the total amount and the sky coverage of high-velocity gas are greater at negative velocities than at positive velocities.

2.2. Sky coverage

Figure 5 of Chapter 3 shows a number of curves $C(T>T_0)$, defined as the percentage of sky area at which HVCs are found with brightness temperature above a certain limit $T_0$ and velocity higher than a given velocity limit. At the survey limit of 0.05 K, 11% of the sky is covered by gas having $|v_{1r}| > 100 \text{ km s}^{-1}$, an increase of a factor two over earlier surveys (with detection limits of the order of 0.2 K).

Using ultra-violet absorption lines and assuming an element abundance one can probe much lower hydrogen column densities than in the 21-cm emission line. For instance, of the lines that are in the wavelength band of the IUE satellite, SiII $\lambda 1260$ allows to detect material where the hydrogen density is $2 \times 10^{17} \text{ cm}^{-2}$. Therefore the relation between sky coverage and detection limit has been extrapolated from the survey limit of $10^{18} \text{ cm}^{-2}$ down to $10^{17} \text{ cm}^{-2}$ (for a velocity limit of $-100 \text{ km s}^{-1}$). This leads to the prediction that at the level of $2 \times 10^{17} \text{ cm}^{-2}$ between 30 and 60% of the sky is covered by gas having $v_{1r} < -100 \text{ km s}^{-1}$. However, in Danly's (1989) sample there are 19 stars more distant than 1.5 kpc and having $l < 180^\circ$, but in none of these absorption at velocities more negative than $-100 \text{ km s}^{-1}$ is detected. Unless the HVCs have low heavy element abundances this implies that they, at least statistically, are farther away than 1.5 kpc. In a few HVCs the presence of some elements has been proved by means of absorption-line studies of some extragalactic probes. See Chapter 12 for a description.

The search for interstellar absorption lines is clearly a field for further research. Enlarging the sample of distant stars in which interstellar lines at high velocity could in principle have been detected, will make the statistical distance limit more firm and possibly push it farther out. It would of course be even better to find absorption by HVCs. This requires long exposure times, as in practice it is at least 30 km s$^{-1}$ velocity.

2.3. Cloud catalogue

In Chapter 4 the first part of this catalogue several components are known and often already occupying certain regions. Their properties, origins and relations to the large scale structure of the HVCs (and sometimes of the entire Galaxy) are still not yet existing. Data on the HVCs (and sometimes of the entire Galaxy) are still not yet existing.

The catalogue was used to draw some overall conclusions and make in-depth studies of the Anticenter complexes with some data on the HVCs. Further, the survey limits of the velocity of the HVCs (and sometimes also their location in the Galaxy) are still not yet existing.

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3. High-resolution observations

Since Schwarz & Oot (1989) the number of fields have been observed. Seven of these fields have been observed. An M and HVC131+1-2 and analysis is presented for a description.

3.1. Fine structure

Figures 1 and 2 of Chapter 12 of the fields. Immediately of the smallest concentrations in the gas at linear scales it is possible that we exist. This clearly requires a description. The density contrast of the galactic halo gas and of HVCs.
times, as in practice it is necessary to obtain spectra of stars fainter than 15th magnitude with at least 30 km s\(^{-1}\) velocity resolution.

2.3. Cloud catalogue

In Chapter 4 the first homogeneous catalogue of high-velocity clouds is presented. Using this catalogue several complexes and populations are defined. Many complexes were previously known and often already observed in considerable detail. The populations (groups of clouds occupying certain regions in \(l-b,v_{r}\) space) are a new concept; they may have different physical properties, origins and relations to the Galaxy.

To understand the phenomenon of the high-velocity gas properly, it would be useful to make in-depth studies of several of these complexes. Especially a possible connection of the Anticenter complexes with the low-velocity gas in the Taurus Molecular Cloud needs to be more fully studied. Also, the survey data contain much information that could be used to unravel the complexities of the velocity field of complex C. In both cases it is necessary to include (partly not yet existing) data on intermediate-velocity clouds, as many of these overlap in position with the HVCs (and sometimes even show structural similarities).

The catalogue was also used to construct the \(\log N(>S)\) and \(\log N(>\Omega)\) distributions of HVCs. The slopes of these relations can be explained if the HVCs have a mass spectrum \(n(M)dM = N_0 M^{-3/2}dM\), are related to the Galaxy and visible throughout it. The slope of this mass spectrum is similar to that found for HI in the disk (-1.87, Dickey & Garwood 1989) and molecular clouds (-1.6, Scoville & Sanders 1987).

3. High-resolution observations

Since Schwarz & Oort (1981) published the first high-resolution map of a HVC, a large number of fields have been observed at Westerbork, with integration times of 2x12\(^{h}\) and 4x12\(^{h}\). Seven of these fields have now been completely reduced, five fields in the classical complexes A, M and HVC 131+1–200, and two VLVCs. A full description of the observations, reduction and analysis is presented in Chapters 6, 7 and 8.

3.1. Fine structure

Figures 1 and 2 of Chapter 6 are column density and velocity–right ascension maps of six of the fields. Immediately apparent is the existence of much fine structure. Even with a beam of 1' the smallest concentrations are not completely resolved. This means that there is structure in the gas at linear scales less than 0.3 \(D_{\text{par}}\) parsec (with \(D_{\text{par}}\) the cloud distance in kpc).

It is possible that we observe evidence of an interaction of HVCs with nearby disk gas in the field MI (see Sect. 4.2 of Chapter 8). Just as in the case of the Draco Nebula (Rohlfs et al. 1989), the proof remains elusive. Arguments both in favor of and against an interaction exist. This clearly requires hydrodynamical modeling with the aim to predict spatial and velocity structure, linewidths and temperatures, and compare these with observations.

The density contrast can be as high as 4 on scales of 4'. For absorption-line studies of galactic halo gas and of HVCs this introduces a considerable uncertainty in the derivation of
abundances. A small feature which lies right along the line of sight to a halo star may provide a strong optical absorption component, but go undetected in a single-dish radio beam due to beam-dilution effects. Alternatively, a cloud seen in HI but not in absorption could in fact lie in front of the probe star, but be sufficiently filamentary or patchy that the bulk of the gas lies just off the line-of-sight from the pencil beam to the star.

3.2. Linewidths and spin temperature of the gas

At each of the positions in the seven WSRT data cubes a gaussian fit was made to the spectrum. Usually only one component is present, but profiles with 2 or even 3 components are not rare. From the fits one obtains the velocity field of the cloud and the line widths of its profiles.

Figure 3 of Chapter 6 presents six velocity fields. There is much structure, with both smooth gradients and erratic jumps occurring often, just as is observed on large scales in the survey data. The origin of this structure is not understood, but it probably is a mixture of a number of different causes, like projection effects, macro-turbulent motions, and motions guided by an embedding medium or magnetic fields. Attempts to measure magnetic field strengths would be useful in this respect.

The fitted line widths are generally rather small. They have a broad distribution with a typical modal value of 3–6 km s⁻¹ FWHM. In Chapter 8 it is argued from the distribution of widths that the kinetic temperature of the gas is below a few 100 K. A lower limit of 30 K is provided by the measured peak brightness temperatures, thereby considerably improving the previously-known limits to the temperature. In one field (HVC131+1–200) absorption is detected in the spectrum of two unidentified background continuum sources (Chapter 9). The derived spin temperature for the HI is about 50 K, consistent with the limit provided by the peak brightness temperature and that derived from the linewidth, and proving that cool gas is present.

In the high-resolution data no evidence is found for broad lines, indicative of hot gas, except in the case of one unusual VHVC. Part of the width of the broad lines seen with single-dish instruments can only be attributed to beam-smearing effects. However, because the interferometer only recovers 30% of the total HI flux and because the small-scale structure shows large velocity gradients, the missing 70% of the flux must mainly consist of warm gas.

Using the measured linewidths, column densities and sizes, the pressure within the cloud cores is estimated to be of the order of 20000/Dₚ cm⁻³ K cm⁻³ in HVC131+1–200 and M 11. The pressure of the extended envelope is about the same, showing that an equilibrium may exist. However, for the fields in complex A the estimated pressure varies between 10000 and 150000/Dₚ cm⁻³ for different concentrations. The comparison of timescales indicates that this object is young and may not be in equilibrium.

A better determination of background and small-scale pressures is necessary. This requires covering a large part of the string with high velocity resolution at somewhat lower (2'–5') angular resolution and good sensitivity. Differences in the estimated pressures of fine-structure and envelope might be attributed to partial ionization, making it imperative to model the ionization balance.

4. Modelling

In order to assess the origin of HVCs, modeling is necessary, as described below.

The models are constructed as follows:
1) Choose a galactic potential.
2) Inject clouds into the potential, allowing them to evolve from a given mass at the time of formation.
3) Follow the clouds in the gravitational field until they hit the galaxy (after about 10⁷ years).
4) Determine at each time step the velocity field relative to the LSR, flux, etc.

Chapter 5 describes the potential used, and the effects of the gas on the bulge and halo scalelengths. The gas density is given by a double power-law model, with a total surface density of 220 km s⁻¹ at the solar circle.

Cloud evolution is modeled assuming no interactions with other clouds throughout their lifetimes. The velocity field of the gas is described by a combination of infall models. The Cannizzo model describes gas ejection from the disk, while the Cannizzo model is applicable if hot gas is present. The infall model describes gas inflow into the disk, and the variations are described in terms of the mass flow rate and the timescale of the inflow.

The predictions of the model are checked against the observations. The model, especially hard to produce broad velocity lines, does a better job at this, in particular for the complex A. A strong increase in density with a halo is found, especially on small scales within the clouds. The model predicts the presence of hot and cold gas phases, and the presence of ionized envelopes leading to the formation of ionized envelopes in the model, predicting the ratio between the two gas phases as expected.
4. Modelling

In order to assess the implications of the survey data for the understanding of the origin of HVCs, modeling is necessary. Ballistic models have been constructed that are based on the scheme described below. Chapter 5 is a preliminary report on the results of these calculations.

The models are constructed as follows:

1) Choose a galactic potential.
2) Inject clouds into this potential according to some prescription. A prescription consists of drawing from a given distribution a random radius, azimuth, height, velocity vector and mass at the time of formation.
3) Follow the clouds in their orbit until the clouds either disperse or are destroyed, for instance when they hit the galactic disk.
4) Determine at the end of the calculation the observables longitude, latitude, velocity relative to the LSR, flux, area and brightness temperature.

Chapter 5 describes the chosen galactic potential. It consists of a bulge, halo and disk. The bulge and halo scalelengths are 300 and 2700 pc, respectively (van der Kruit 1986). The disk density is given by a double exponential with radial and vertical scalelengths of 5 kpc and 325 pc, respectively, and total surface density at the sun of $75 M_\odot$ pc$^{-2}$. This gives a rotation velocity of 220 km s$^{-1}$ at the solar radius (8.5 kpc).

Cloud evolution is modelled in a very simple way: they are assumed to be pressure-confined throughout their lifetime and therefore always keep the same size. Only when clouds hit the gaseous disk are they assumed to be destroyed. At formation a mass is given to each cloud, chosen from a power law spectrum $n(M)dM = N_\alpha M^\alpha dM$. Assuming the same average density for all clouds makes it possible to calculate the cloud radius. Together with the cloud distance this allows to calculate the cloud flux, brightness temperature and area. By comparing the observed distributions of flux and area with the model distributions it follows that $\alpha = -1.5$ and that the density, averaged across the whole cloud, is of the order of 0.005 cm$^{-3}$.

The different types of model are characterized by different prescriptions for the injection scheme. Various possibilities exist, which can be put into two categories: galactic models and infall models. The Cannonball and Fountain model are of the galactic type. The Cannonball model describes gas ejected from the disk by means of supernova explosions. The Fountain model is applicable if hot, ionized gas rises upward from the disk, cools and recombines. Two variations are described in Chapter 5: a parametrized model and one in which the positions and velocities of newly formed cool neutral clouds in a hydrodynamical flow calculation are used.

The predictions of the Cannonball model do not resemble the observed distributions. It is especially hard to produce high-velocity clouds at high galactic latitude. The Fountain model does a better job at this, but still can not explain the very-high-velocity clouds and the Anticenter complexes. A strong argument in favor of the Fountain model is the observed fine structure on small scales within the HVCs. The random velocity jumps combined with the presence of a warm and a cold gas phase are easy to understand within the framework of this model, where instabilities leading to the formation of cool neutral cores embedded within warmer, partly ionized envelopes are predicted to occur. It is necessary to do more theoretical work aimed at predicting the ratio between ionized and neutral material, and the kind of structure that can be expected.
Three infall-type models are described in Chapter 5: the Pure Infall model, in which a small number of objects continuously flows in from intergalactic space; the Local Group model, in which clouds are assumed to have the velocity distribution of nearby (D<300kpc) dwarf galaxies; and the Circular Motion model, in which clouds can remain in orbit around the Galaxy for a Hubble time. In each of these models very-high-velocity clouds are predicted to occur. They owe their velocity to the acceleration imparted by the Galaxy. No model gives a fully satisfactory fit of the celestial and velocity distributions. It is possible to reproduce the Anticenter complexes, but only if one of the more massive clouds in the population happens to be at the proper place at the present time. A major problem with any of these infall-type models is that the observed North-South asymmetry is never reproduced.

A very simple model in which the Magellanic Stream is seen as the source of the clouds is able to reproduce the North-South asymmetry very easily. Our model is too simplistic to provide a proper fit, but indicates that this type of model is promising.

These model calculations have shown conclusively that the fact that in the first two longitude quadrants mainly negative velocities are observed, while in the third and fourth quadrants mainly positive velocities occur, is due to a reflection of the rotation of the LSR around the galactic center. Further, the existence of the two overlapping complexes of HVCs in the Anticenter region is very hard to reproduce by the ballistic calculations. The North-South asymmetry in the distribution of VHVCs is only found in the model where the Magellanic Stream is the source of the gas. In all infall-type models VHVCs are predicted to occur in large numbers also in the northern hemisphere. To strengthen these conclusions and obtain better fits more work is clearly needed.

It seems very likely that the observed distributions of $l$, $b$, $v_{lsr}$, flux and size can only be reproduced by a combination of two or more models, and hence that there are several sorts of HVCs, with different origins.

5. Concluding remarks

Based on the data and models presented in this thesis, the following set of explanations seems be the most promising: The Magellanic Stream is a tidal tail drawn out of the Magellanic Clouds by the Galaxy during their last passage (see Murai & Fujimoto 1980). The VHVCs observed in the southern galactic hemisphere are shreds of the Stream that were disconnected long ago (as proposed by Giovanelli 1981). Other clouds are part of a galactic fountain in which galactic disk gas is heated, rises to large heights above the plane, cools, condenses into neutral hydrogen again, and then falls back to the plane ballistically (Field 1965, Bregman 1980, MacLow et al. 1989). Complex C is either part of the fountain or a high-$z$ spiral arm (Davies 1972, Verschuur 1973) (these two explanations need not be mutually exclusive). A number of clouds near the galactic antecenter and center probably consist of material streaming toward the Galaxy, as Mirabel (1982, 1989) has advocated for several years. The source of this infalling material still remains unclear, as it may be gas coming from nearby intergalactic space, from the Local Group, or even from the Magellanic Stream. Elsewhere on the sky other H I clouds should be present that are members of the same population, but are observationally inseparable from the clouds belonging to the galactic fountain.

Many problems pose no direct distance determination from whole-sky maps to correct observations to measure radial velocities to obtain high-resolution coherent elements at the HVC velocity limit described in Sect. 2.

To understand the spatial structure of the clouds, this should aim at the proper model and relations of the model to the structure. Such models should be based on a coherent model, which can provide a physical description of the magnetic strengths within HVCs and other structures. The ballistic models provide only a better description of the HVCs, and a description of cloud evolution and the influence of drag forces is needed.

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Many problems posed by the HVCs remain unsolved. The major problem is still that no direct distance determinations are available. To solve this it will be necessary to use the whole-sky maps to correlate possible probes with the high-velocity gas, to use high-resolution observations to measure a better value of the column density in the direction of the probe, and to obtain high-resolution optical or ultra-violet spectra to search for absorption lines from heavy elements at the HVC velocity. It would also be useful to improve upon the statistical distance limit described in Sect. 2.2, by enlarging the sample of randomly chosen distant probes.

To understand the small-scale structures better, hydrodynamical modelling is in order. This should aim at the prediction of observable parameters, like linewidths, temperatures and structure. Such models may then also be used to give constraints on the Galactic Fountain model, which can provide the initial conditions for these models. Probably it is necessary to include magnetic forces. Therefore, attempts at measuring values of or limits to magnetic field strengths within HVCs are useful.

The ballistic models described in Chapter 5 still need improvements and extensions. A better description of the \( \beta - v_{\perp} \) distribution of the VHVCs must be searched for. Further, the influence of drag forces on cloud motion should be studied, and we need an improved description of cloud evolution.

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