HIGH-VELOCITY CLOUDS

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HIGH-VELOCITY CLOUDS

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PREFACE

On the occasion of the retirement of Ulrich Schwarz, a symposium was held in Groningen in May of 1996, celebrating his contributions to the study of the interstellar medium, including his work on the high-velocity clouds. The coming together of many specialists in the latter field prompted the idea of compiling a book containing their contributions, and summarizing the status of our understanding of the high-velocity cloud phenomenon.

This seemed especially worthwhile at the time, since many exciting developments were taking place. After the discovery of some H I clouds with high velocities, about 40 years ago, the subject had been dominated by 21-cm observations of H I emission. Starting in the mid-1980s much progress was being made because of the availability of new instruments, such as large ground-based optical telescopes and UV observatories in space. The connections between the work on high-velocity clouds and other studies of the properties of the (hot) interstellar medium also became clearer.

Progress in the study of high-velocity clouds has been especially marked in the years between 1998 and 2003, during which time the Leiden-Dwingeloo Survey and *HIPASS* H I surveys became available, many extragalactic high-velocity cloud analogues were found, Hα measurements finally became practical, molecular hydrogen was discovered in IVCs, the first distances and metallicities were obtained, many highly-ionized high-velocity clouds were discovered by observing the O VI absorption lines with *FUSE*, and the model proposing an origin of the clouds in the Local Group was put forward, vigorously discussed, and analyzed in detail. With these new results, the high-velocity clouds moved from the category of peculiar phenomena to a place of significance in the study of the structure and evolution of the Milky Way and of other galaxies.

All authors were quick in their response to our request to write a chapter for this book, but some took a considerable time to complete their contribution (including some of the editors). For this and many other reasons, putting together this book took much longer than anticipated. Meanwhile, many important developments took place, and the editors had to request a complete rewrite of some chapters. We would like to thank the authors of those chapters (8, 9, 11, and 15) for their forbearance, and appreciate their extra effort. In one case (chapter 14) a rewrite turned out to be impractical, and the chapter is still in the form in which it was originally delivered in January 1999.

All authors were asked to (and did) update their texts in late 2003 and 2004, to incorporate the most recent developments in their respective subfields. In the later stages, authors had access to the other chapters, allowing a fair amount of homogenization. Yet, each chapter reflects the author's views and conflicting thoughts on the HVC phenomenon have not been polished away. This makes the present book, the editors hope, an up-to-date account of the understanding of the phenomenon of high-velocity clouds in the Milky Way Halo and elsewhere, and therefore a much more valuable overview than it would have been if it had been finished a few years back, as was originally planned.

The editors like to express their gratitude to all of the authors contributing to this volume. It is their confidence in the final product which made it all work. We also thank the publishers, notably Harry Blom, for their patience and encouragement. A book is easily conceived but the making of it requires foremost endurance.

April 2004

1. HISTORY OF HVC RESEARCH – AN OVERVIEW

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Abstract. The discovery of gas clouds at high velocity outside the disk of the Milky Way dates from the middle of the 20th century. Since their discovery, numerous new techniques and new instruments have allowed great strides in the understanding of the high-velocity cloud phenomenon. This chapter presents a review of these developments, organized by period (five sections each covering about one decade), and within each period summarizing the progress in each of several subfields, such as radio surveys, UV observations, and theories.

1. Discovery; research until 1963

Studies in the late 1930s had revealed multiple interstellar absorption components in spectra of early-type stars (Beals 1938). In his survey of interstellar absorption lines in 300 stars, Adams (1949) found eight stars at $b{>}{+}20^\circ$ with absorption at velocities $|v_{\rm LSR}|{>}20$ km s^{-1} relative to the Local Standard of Rest (LSR). Then Guido Münch started a program to systematically observe distant stars at high galactic latitude, using the Mt. Wilson 100-inch Coudé spectrograph. First results for the high-latitude star HD 93521 (Münch 1952) revealed four separate clouds, with velocities up to -50 km s^{-1}. The full project data appeared much later (Münch & Zirin 1961), showing many absorption components at velocities substantially different from the 0 km s^{-1} expected from differential galactic ro-

H. van Woerden et al. (eds.), High-Velocity Clouds, 1–24

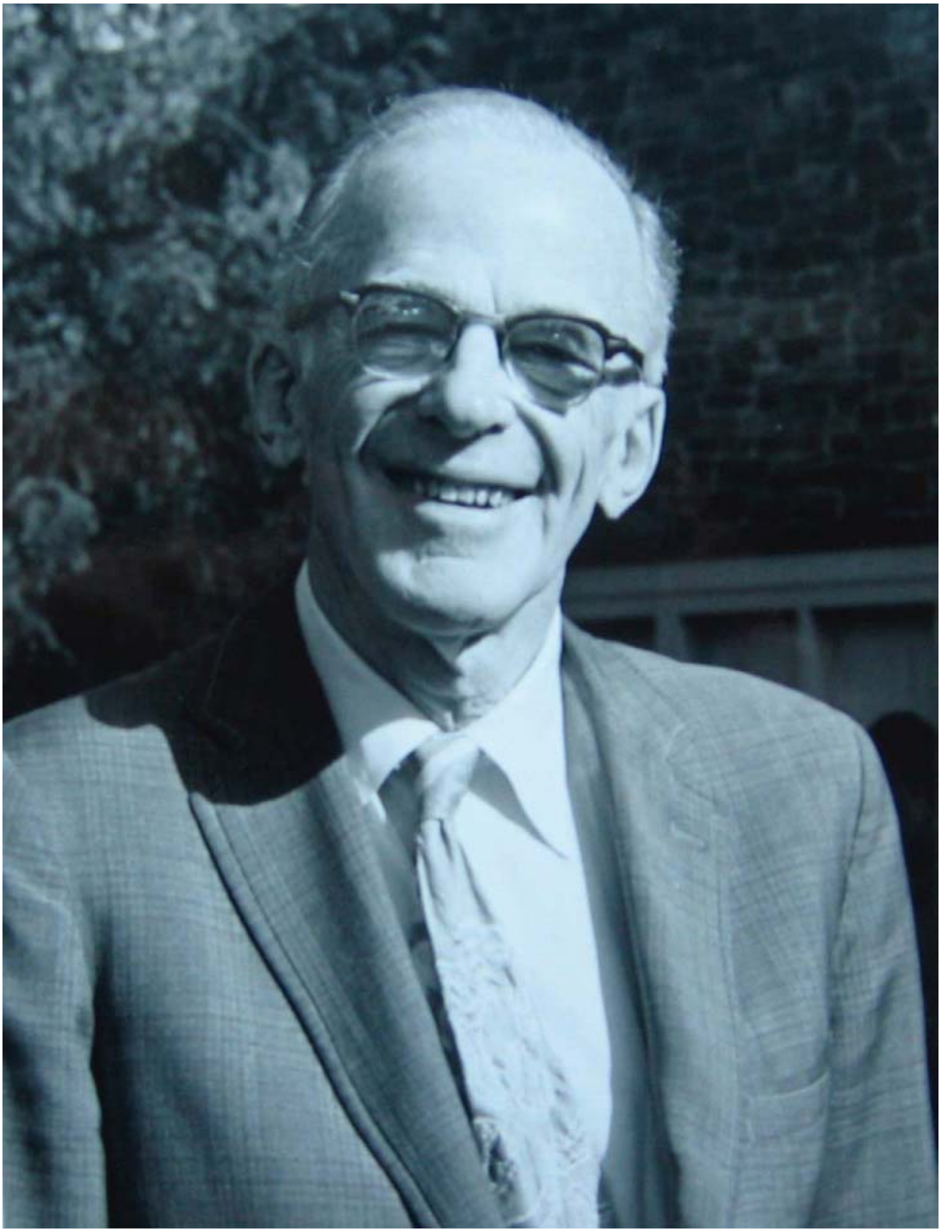

Figure 1. Lyman Spitzer, Jr. (1914-1997) in 1989.

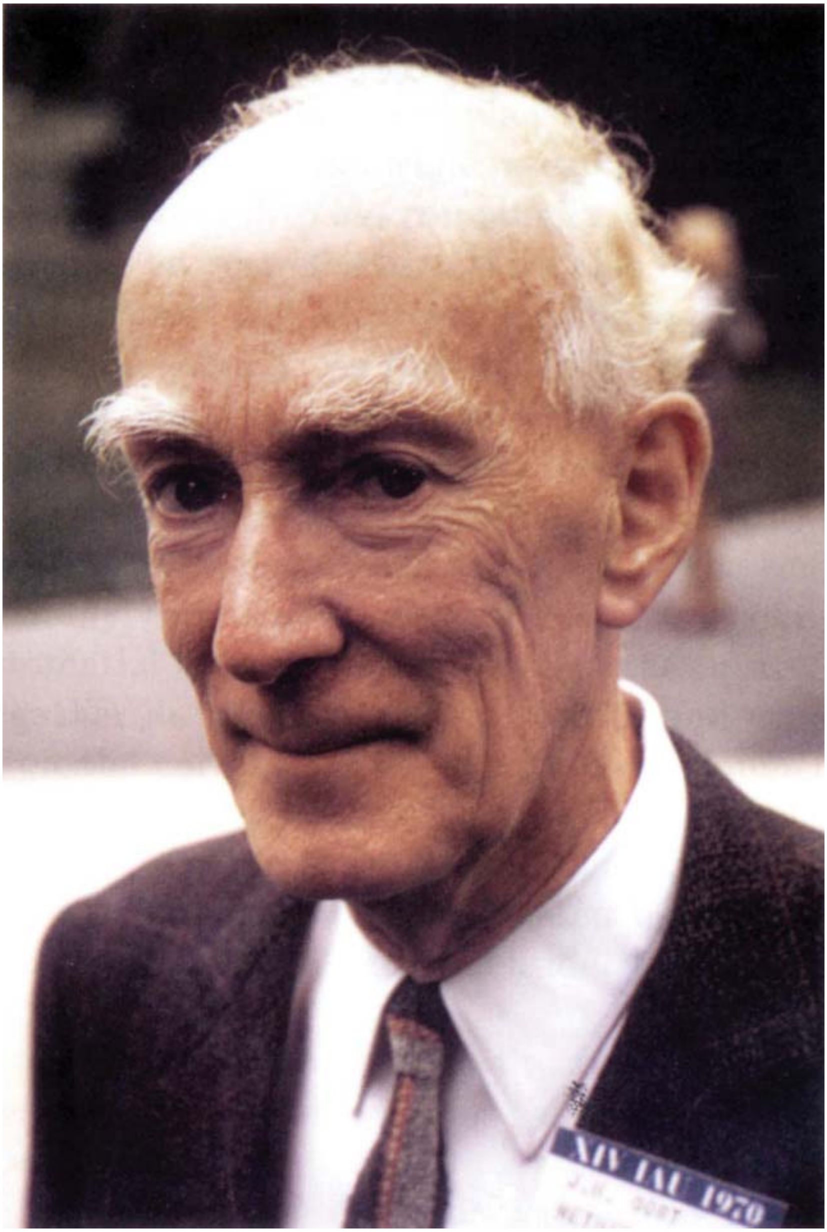

Figure 2. J.H. Oort (1900-1992) in 1970.

tation for nearby galactic gas. These absorptions were called *high-velocity clouds* (HVCs), which at the time referred to interstellar gas with velocities differing by more than 20 $km\,s^{-1}$ from the LSR (e.g. Schlüter et al. 1953). A circumstellar origin was suspected for many such lines in the spectra of O and B stars.

In those years, Lyman Spitzer regularly visited Mt. Wilson, and he was generally well informed about the work going on there. As related by Münch (see de Boer 1989), when Spitzer learned of Münch's findings, he surmised that if clouds of apparently neutral gas were present away from the Milky Way disk, a gaseous medium outside the disk should exist to pressure-confine these clouds. However, the confining gas had to be highly ionized, or it would have shown up in metal absorption lines too. Assuming hydrostatic equilibrium, Spitzer concluded that there should be gas with a temperature up to 10^6 K several kpc above the disk. Since very hot gases were at that time known only from the coronas of stars, Spitzer dubbed this gas the *Galactic Corona*, and he described the essence of this model in a very influential paper (Spitzer 1956). In it, he speculated that with further development of satellite techniques (Sputnik would be launched in 1957) high-resolution spectra in the ultraviolet might reveal the presence of absorption lines of Si IV, C IV, N V, and O VI. The physics of the Galactic Corona and questions about the required observations to study those gases showed up in Spitzer's class exercises for many years thereafter (Savage, priv. comm.). Exactly 40 years after the first paper on the Galactic Corona, Spitzer (1996) summarized his views of all the developments up to then.

2. Early radio research: 1963–1968

The first survey of Galactic H I was done from 1952 to 1955 with the 7.5-meter Kootwijk telescope in the Netherlands, complemented by data for the southern sky from a 36-ft aerial in Sydney, Australia. The results clearly showed the presence of differential galactic rotation and spiral arms (Oort et al. 1958).

Following the prediction by Spitzer (1956) that there should be a Galactic Corona, Oort suggested to van Woerden that such a corona might contain neutral hydrogen with velocities up to 100 $km\,s^{-1}$, and that such hydrogen might replenish the gas seen to be expanding away from the Galactic Center (van Woerden et al. 1957). Early searches were started by Raimond in 1958, using the then just 2-year old 25-m *Dwingeloo* telescope (shown in Fig. 3). These were unsuccessful, because of insufficient sensitivity (a brightness temperature detection limit of ∼2 K). A few years later, however, new receiver technology led to several detections of H I with velocities

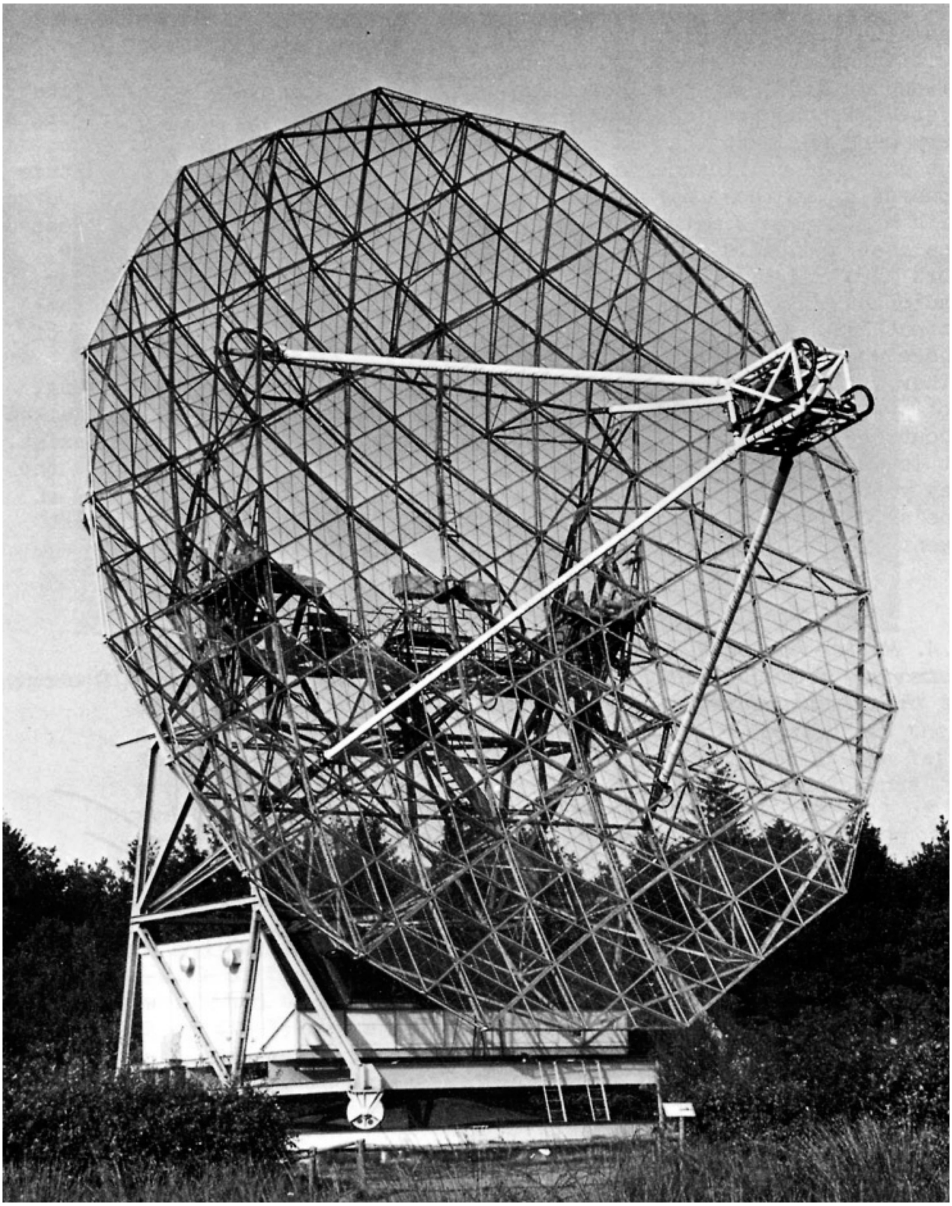

Figure 3. The 25-m Dwingeloo telescope in 1973. Photo: ASTRON.

of -110 to -175 km s^{-1} (Muller et al. 1963). These HVCs are now known as parts of core C I, and cores A IV and B. The paper was published in a relatively obscure journal (the Comptes rendus de l'Académie des Sciences de Paris), because of its very short publication time (a few weeks). A reproduction of this discovery paper is shown in Fig. 4.

C. R. Acad. Sc. Paris, t. 257, p. 1661-1662 (2 septembre 1963). Groupe 3.

RADIOASTRONOMIE. — *Hydrogène neutre dans la couronne galactique ?* Note de MM. **Christiaan Alexander Muller**, **Jan Hendrik Oort** et **Ernst Raimond**.

En utilisant un amplificateur paramétrique quasi-dégénéré en tête de notre récepteur à huit canaux et du radiotélescope de 25 m de Dwingeloo ([1]), Pays-Bas, nous avons observé des profils de la raie 21 cm s'étendant de — 175 km/s jusqu'à + 175 km/s de vitesse radiale. Ces profils ont été relevés tous les 5 degrés en longitude et aux latitudes de — 40 et + 40°. La bande passante utilisée est de 20 kc/s (4,2 km/s).

En quatre endroits, des nuages d'hydrogène neutre ayant des vitesses supérieures à 100 km/s ont été détectés. On trouvera dans le tableau ci-dessous les coordonnées, la vitesse radiale moyenne, la demi-largeur et la température de brillance des maximums observés. Chaque maximum a été déterminé par deux mesures indépendantes. La vitesse radiale est mesurée par rapport au système local de référence, qui est défini par le mouvement moyen du gaz interstellaire dans le voisinage du Soleil. L'unité de température de brillance est approximativement 1°K. La dernière colonne du tableau donne le nombre d'atomes d'hydrogène présents dans une colonne de 1 cm² de section.

l^{II} (degrés).	b^{II} (degrés).	l^{I} (degrés).	b^{I} (degrés).	V_r (km/s).	W (km/s).	T_b (unités).	N (cm^{-2}).
83,42	+40,68	50	+40	—116	27	1	5.10^{19}
88,47	+40,56	55	+40	—116	23	1	4 »
153,20	+38,99	120	+40	—174	25	4	20 »
167,95	+38,74	135	+40	—152	25	1,5	7 »

Le diamètre à demi-intensité du nuage à $l^{I} = 120°$ est de 2°. Les dimensions angulaires des autres objets n'ont pu encore être déterminées. Pour l'instant, on peut avancer que le rayonnement observé à $l^{I} = 50°$ et $l^{I} = 55°$ est probablement émis par un même nuage. L'objet observé à $l^{I} = 135°$ n'a pu être détecté aux longitudes 130 et 140. Par conséquent, sa dimension angulaire est limitée à moins de 10° en longitude.

Dans quelques semaines, des observations permettant de déterminer les dimensions seront disponibles. Un programme d'observation pour la recherche d'objets à grande vitesse dans d'autres parties du ciel est également entrepris.

Il n'y a actuellement pas de possibilité de mesurer les distances. Si les nuages étaient des objets proches et de courte vie situés près du plan galactique, leur nombre serait étonnamment élevé. Par conséquent, nous tendons à conclure que les objets observés sont situés dans la couronne de notre galaxie. Toutefois, la grande dispersion de vitesse observée dans les nuages est un phénomène intriguant.

(2)

En plus des résultats donnés ci-dessus, les profils montrent plusieurs maximums et de longues ailes indiquant des vitesses allant jusqu'à ± 70 km/s. Certains de ceux-ci s'étendent en longitude sur des dizaines de degrés, si bien qu'ils sont probablement peu distants. Une étude de ces particularités est entreprise par les observatoires de Groningue et Leyde.

(1) H. VAN WOERDEN, K. TAKAKUBO et L. L. E. BRAES, *B. A. N.*, 16, 1962, p. 323.

(Observatoires de Dwingeloo et de Leyde, Pays-Bas.)

Figure 4. Reproduction of the paper announcing the discovery of high-velocity H I (Muller et al. 1963). Note that the table shows positions in both old (l^I,b^I) and new (l^{II},b^{II}) galactic coordinates. The survey was done at five-degree steps in longitude at old-style latitude b^I=40°. Print supplied by E. Raimond.

Not long thereafter, Smith (1963) found a cloud with v=+90 km s^{-1} at (l,b)=(40°, −15°), currently also known as complex GCP (see Wakker & van Woerden (1991) for current HVC nomenclature), while Dieter (1964) found high-velocity gas near the South Galactic Pole, using the *Hat Creek* telescope. In the years after the discovery, astronomers from Leiden and Groningen used the *Dwingeloo* telescope to make a systematic search for high-velocity H I on a 10°×10° grid at latitudes >+20°. During the course of this survey, gas at velocities between −50 and −100 km s^{-1} was also found in many directions.

A division of labor was decided upon. Leiden astronomers would analyze the high-velocity gas ($v_{\rm LSR}$<−80 km s^{-1}), while those at Groningen would concentrate on the "intermediate-velocity clouds" (IVCs). This work led to a classic series of papers in the BAN (Blaauw & Tolbert 1966, Hulsbosch & Raimond 1966, Oort 1966), with Oort discussing possible origins of the HVCs: (a) nearby supernova remnants (he considered this unlikely); (b) condensations formed in a gaseous corona at high temperature; (c) clouds ejected from the Galactic Nucleus; (d) clouds ejected as cool clouds from the disk; (e) intergalactic gas accreted by the Galaxy; (f) small satellites of the Galaxy or independent galaxies in the Local Group. With the addition of (g) material tidally extracted from the Magellanic Clouds, this is still a good summary of the possible origins of HVCs, forty years later. In 1966, high-velocity gas found a place in the program of IAU Symposium 31, "Radio Astronomy and the Galactic System" (van Woerden 1967).

3. Developments 1968–1980

Following the discovery and early surveys, the decade from 1968 to 1980 saw much effort devoted to radio observations of the high-velocity H I. Little effort was put into the IVCs; Wesselius (1973) and Wesselius & Fejes (1973) completed the analysis of a *Dwingeloo* survey of the northern sky made by Tolbert (1971), but no further progress was made until the mid-1990s. On the other hand, surveys for the HVCs became ever more complete and many individual clouds were mapped in detail, while several papers put forward arguments for variants of Oort's suggested origins.

A small but steady stream of papers on HVCs kept appearing in these years (on average 6 a year), including a paper in the Annual Reviews (Verschuur 1975). In 1973 and 1978 there were special sessions on HVCs during IAU Symposia – No. 60 on Galactic Radio Astronomy (Kerr & Simonson 1974) and No. 84 on The Large-Scale Characteristics of the Galaxy (Burton 1979). In general, however, HVCs were only studied by a small number of astronomers, and they were considered something of a curiosity.

3.1. H I SURVEYS

Following the early surveys, sky coverage was quickly improved to a $5^\circ \times 5^\circ$ grid for declinations $>-35^\circ$, leading to the first thesis on HVCs (Hulsbosch 1973). Over the next few years, many new clouds were discovered. Using the *Parkes* 60-ft, Mathewson et al. (1974) showed that the gas found near the South Galactic Pole by Dieter (1964) was part of a chain of clouds starting from the Magellanic Clouds, henceforth called the Magellanic Stream. Mathewson (1967) found a cloud at l=165°, b=+60°, which was named cloud "M" after him. Van Kuilenburg (1972a, b), exploring the southern galactic hemisphere, discovered gas with velocities <-150 km s^{-1} near the Anti-Center. Wannier et al. (1972) discovered widespread, faint positive-velocity gas in the region l=250° to 320°, b=+10° to +30°. By then the number of known HVCs had grown to the point that a scheme was adopted in which each cloud was given a name based on its galactic longitude, latitude and LSR velocity, e.g. HVC 165+55−150. Thus, by 1973 a fairly complete, but rough picture of the high-velocity sky existed, with varying sensitivity and grid in different parts of the sky.

Using a much improved receiver system at the *Dwingeloo* telescope, Hulsbosch (1978) mapped part of the Anti-Center region in detail, on a $1^\circ \times 1^\circ$ grid, with a $36'$ beam. The difference with earlier surveys was that a much larger velocity range was searched (-500 to $+500$ km s^{-1}), although at a velocity resolution of just 16 km s^{-1}, and that 15-minute integrations were used, giving a 5-σ detection limit of 0.05 K, or $\sim 2\times10^{18}$ cm^{-2} for a typical 20 km s^{-1} wide line. This was a factor $\sim$5 better sensitivity than any previous survey, a factor 2 to 3 broader velocity coverage, and a factor 4 greater sky coverage. Many new HVCs were discovered, including some with very high negative velocities (<-300 km s^{-1}), which were named the

VHVCs. At that time it was decided to extend this survey to almost the whole sky observable from Dwingeloo (declinations $>-17.^\circ2$). Because of limitations in computing power and memory (the data were reduced on a PDP 11/70 with 32 kbyte of RAM and 1 Mbyte disks), only the velocity and peak brightness temperature of each identified high-velocity profile component were saved. By 1980 observations were progressing rapidly.

In the same period, an unbiased survey of most of the northern sky (declinations -18 to $+55^\circ$) was carried out by Giovanelli (1980, 1981), using the 300-ft *Green Bank* telescope ($9.'7$ beam) on a $1^\circ\times2^\circ$ grid in right ascension and declination, with a velocity range of -900 to $+900$ km s^{-1}. This survey established that a) HVCs are only found at LSR velocities between -450 and $+350$ km s^{-1}, b) there are two populations of HVCs (the large complexes and the VHVCs, which stand out in a longitude-velocity plot), and c) a pronounced north-south asymmetry is present in the distribution of the HVCs. Giovanelli (1981) also argued that the angular and velocity distribution of the VHVCs is incompatible with that of Local Group galaxies, as well as incompatible with a location in the Galactic Disk. He concluded that they are likely either shreds of the Magellanic Stream or other objects orbiting the Galaxy.

3.2. DETAILED MAPPING

The period 1968 to 1980 also saw many papers with maps and analyses of individual clouds, at angular and velocity resolutions much higher than those of the surveys. One of the more important of these was the study by Giovanelli et al. (1973), who used the *Green Bank* 300-ft to map large parts of clouds A, C, M, and HVC 131+1−200 (currently also known as complex H) at intermediate ($10'$) angular resolution, showing that much structure is present, and discovering multiple cores, which they named A I, A II, A III, A IV, A V, C IA, C IB, C IC, C IIIA, C IIIB, C IIIC, M I, M II, M III. [Core C II is at lower velocities (~-80 km s^{-1}), and at the present time is considered part of the IV Arch, specifically core IV 8.]

From these and other maps with $10'$ beams and 1 km s^{-1} velocity resolution, covering degree-scales, several authors concluded that the brightest HVCs show a core-halo structure (Davies et al. 1976; Giovanelli & Haynes 1977). This was interpreted as evidence for the presence of the standard two phases of the ISM – a cold phase, with temperature $\sim$100 K and density $\sim$1 cm^{-3}, and a warm phase, with temperature $\sim10^4$ K and density $\sim$0.01 cm^{-3} (Field et al. 1969). Both of these would then be confined by the external pressure of the hot Galactic Corona proposed by Spitzer.

High-resolution maps of the cores made with interferometers started appearing in the mid-1970s (Greisen & Cram 1976, Schwarz et al. 1976;

Schwarz & Oort 1981). Especially the maps made with the new Westerbork Synthesis Radio Telescope (*WSRT*) showed the presence of much small-scale structure, down to the 1′ resolution.

3.3. DISTANCES AND ABUNDANCES

Hypotheses for the origin of HVCs proliferated in this decade (see Sect. 3.5). Most of the proposals provided reasonable fits to some parts of the clouds' sky and velocity distributions, even though these models were very different. Predicted distances ranged from a few kpc to several hundreds of kpc. Discriminating between the models clearly required HVC distances and metallicities, which were completely lacking. That distances and metallicities held the key to understanding HVCs had been clear since their discovery. It had also been clear that deriving distances required high-resolution absorption-line spectra of faint background stellar targets with known distances. An early attempt was published just a few years after the discovery of HVCs (Prata & Wallerstein 1967). This study concentrated on the Ca II K line, which together with Na I D is the only useful line in the optical. Unfortunately, both these interstellar lines tend to be weak in HVCs.

The early failure to detect absorption from HVCs, together with their possible intergalactic origin, led some authors to suggest that they are primordial (Z=0) gas. Due to a lack of known good background probes, the absorption-line studies languished for many years, with no positive results (detections), nor significant negative results (non-detections giving limits).

3.4. UV AND X-RAY DATA; THE "GALACTIC FOUNTAIN" CONCEPT

After the 1956 paper, Spitzer pushed to get access to the UV part of the spectrum in order to observe the highly-ionized gas in the predicted Galactic Corona. This led to the development of the *Copernicus* satellite. Launched in 1973, it gave access to the 900 to 3000 Å spectral range, which includes the O VI, N V and C IV absorption lines. However, the tracking capability of that satellite was limited to stars brighter than $V\simeq6.5$ mag, so that spectra could be obtained essentially only for nearby galactic stars. These showed the presence of O VI with $v_{\rm LSR}\sim0$ km s^{-1} in all directions (Jenkins & Meloy 1974). One of the more distant stars observed, HD 93521, indicated the presence of O VI in the halo, at $v_{\rm LSR}=-50$ km s^{-1} (Jenkins 1978).

The 1970s also saw important developments in X-ray astronomy. First scans with rocket-borne X-ray detectors showed the presence of considerable diffuse X-ray emission (Williamson et al. 1974).

Together, the widespread O VI and diffuse X-rays led to the need to include the hot (10^6 K) phase in the models of the ISM in the Disk. This hot phase was thought to be produced by supernova explosions, leading to outflows from the disk. Once in the halo the hot gas could cool, condense, and might fall back to the Milky Way disk as HVCs, establishing a "Galactic Fountain" (Shapiro & Field 1976). In a first theoretical exploration of the kinematics, the estimated back-flow velocities were compared with observed HVC velocities and appeared to be largely in agreement (Bregman 1980).

The 1978 launch of the International Ultraviolet Explorer (*IUE*) satellite with its echelle spectrographs enabled measurements of the absorption lines of the high ions C IV and N V over long sight lines for large numbers of stars. Fe II, Mg II, etc. absorption was detected in an HVC at $+120$ km s^{-1} against background stars in the LMC. Interestingly, this HVC also showed C IV absorption (Savage & de Boer 1979). Spitzer et al. (1980) concluded that this was the first sign of the highly-ionized halo gas he had proposed in 1956. A first determination of metal column densities of the HVCs on the LMC sight line showed the metal content of the gas to be relatively high, but the weakness of the 21-cm emission prevented giving hard values (Savage & de Boer 1981). The z-extent of the C IV gas was found to be several kpc. Further, the Magellanic Clouds also appeared to possess an envelope of coronal gas (de Boer & Savage 1980; de Boer 1984).

3.5. HYPOTHESES FOR THE ORIGIN OF HVCS

After Oort's (1966) original summary of possible origins for the HVCs (see Sect. 2), many new ideas were put forward. These tended to concentrate on explaining complexes A and C. Wakker & van Woerden (1997) summarized and criticized each of these proposals, counting eighteen different models. The most well received of these were the following.

(a) The idea of Oort (1970) that the HVCs represent the last stage of condensations in a hot Galactic Halo, left over from the formation of the Milky Way, and now at distances ~1 kpc above the plane. This was worked out in more detail in the paper by Oort & Hulsbosch (1978), in which they predicted a z-height of 1 kpc and a metallicity of 0.7 solar for HVC complex A.

(b) The proposals by Verschuur (1973) and Davies (1974) that some HVCs are part of the outer galactic spiral structure; this related complexes A, C and the Outer Arm. This model was worked out in detail in the review paper on HVCs by Verschuur (1975).

(c) The analysis by Bregman (1980), which views the HVCs as the return flow of a Galactic Fountain as proposed by Shapiro & Field (1976), at distances of a few kpc above the plane; this was considered very attractive because it provided a possible physical mechanism for generating HVCs.

(d) The proposal by Mirabel (1982) that the high-negative-velocity clouds in the general direction of the Galactic Center and Anti-Center represent infall to the Milky Way.

(e) The Magellanic Stream was explained as a tidal bridge and tail of gas pulled out from the Magellanic Clouds, although there were many competing ideas about the details of this process. Around 1980, the debate was about whether the Stream is a leading or a trailing feature; the most notable papers presenting tidal models being Fujimoto & Sofue (1976), Murai & Fujimoto (1980) and Lin & Lynden-Bell (1982).

4. Developments 1981–1991

This decade saw the culmination of the earlier radio efforts, which would pave the way for the work in the decade thereafter. Specifically, the completion of Hulsbosch's survey of the northern sky, and the high-angular-resolution observations of Schwarz & Oort (1981) and Wakker & Schwarz (1991). Optical and UV absorption-line studies of background targets of HVCs and of the hot Galactic Corona started to bear their first fruits. Most of the proposed models remained alive, though some were oversold and others remained underappreciated. The number of refereed papers concerning models or observations of the HVCs stayed about constant at an average of 7 per year. Four HVC-specific sessions were included in conferences – at the 1983 IAU Symposium 106 (The Milky Way Galaxy) in Groningen (van Woerden et al. 1985), in the 1985 NRAO workshop The Gaseous Galactic Halo, held in Green Bank (Bregman & Lockman 1986), at the 1989 IAU Colloquium 120, Structure and Dynamics of the Interstellar Medium, held in Granada (Tenorio-Tagle et al. 1989) and in IAU Symposium 144, The Interstellar Disk-Halo Connection in Galaxies, held at Leiden in 1990 (Bloemen 1991). The proceedings of the last of these gives a useful summary of the state of HVC research in the late eighties.

4.1. SURVEYS

The observations for Hulsbosch's *Dwingeloo* HVC survey (see Sect. 3.1) were finished in 1982, but several more years of mopping up passed, and Hulsbosch left astronomy. Wakker then prepared this survey for publication, resulting in the Hulsbosch & Wakker (1988) catalog. As the *Dwingeloo* survey was nearing completion, Argentinian astronomers used the 30-m dish at Villa Elisa for the first systematic HVC survey of the southern sky, with parameters chosen to match the northern survey, albeit on a $2^\circ \times 2^\circ$ grid (Bajaja et al. 1985). They followed this by more detailed mapping of individual clouds (Bajaja et al. 1989). Combining the northern and southern data, Wakker & van Woerden (1991) produced the first all-sky HVC catalog. In this catalog they decided to name the HVC complexes and number the clouds, rather than using the l,b,v notation, since for many clouds and complexes it is not clear whether one should use the brightest core, the average for the cores, a position-weighted average or an intensity-weighted average to determine the l,b,v name. Thus, HVC complexes D, G, H, L, WA, WB, WC, WD, GCN and GCP came into existence. "D" and "L" were named after the constellations Draco and Libra, in which they lie. "H" was named after Hulsbosch, "G" is near the galactic plane and close to "H", "GCN" and "GCP" are near the Galactic Center. The "WA" through "WD" clouds are the positive-velocity complexes discovered by Wannier, Wrixon & Wilson (1972) – the author names of the discovery and naming papers all start with "W". Each cloud was also given a "WW" number in the catalog by Wakker & van Woerden (1991).

The *Dwingeloo* survey also led Wakker (1991) to propose a new definition for the HVCs, based on the "deviation velocity". This is the difference (negative or positive) between the observed velocity and the maximum radial velocity that can be understood from a simple model of galactic rotation. Defining HVCs in this manner allows one to eliminate clouds with $|v_{\rm LSR}|>100$ km s^{-1} near the galactic plane, while at the same time including clouds with $|v_{\rm LSR}|\sim 90$ km s^{-1} at high galactic latitude.

4.2. DETAILED MAPPING

The results that Schwarz & Oort (1981) obtained by mapping core A I at $1'$ and 1 km s^{-1} resolution using the *WSRT* led to the hope that such maps contained the key to understanding the internal physics of the clouds. As a result, a number of cores and small clouds were mapped in detail, which became the basis for Wakker's (1990) Ph.D. thesis. However, deriving physical parameters proved difficult, especially since the estimates depend on the assumed distance. Nevertheless, it was shown that the brighter cores have a hierarchical structure, and that column density variations of up to a factor a few exist on arcminute scales. Wakker & Schwarz (1991) also considered that the velocity field for two small VHVCs mimicked the rotation of a self-gravitating cloud. They rejected this as an explanation because it implied distances of several 100 kpc, and an average H I volume density of 10^{-3} cm^{-3}, small enough to expect that the clouds would be mostly ionized, in which case the calculations are no longer valid.

One important finding from the high-angular-resolution work was that HVC cores show structure down to (and below) 1 arcminute scales, implying that accurate determinations of the H I column density in the direction of background probes require a high-resolution H I map.

4.3. X-RAY OBSERVATIONS OF THE GALACTIC HALO

Following the earlier discovery of diffuse X-ray emission, further X-ray measurements by the Wisconsin group resulted in the proposal that the Sun was embedded in an X-ray-emitting cavity, the Local Hot Bubble. Others maintained that the emission also contained a component associated with the hot fountain-flow gas in the Halo. Thus the quest was on to find shadows of HVCs against the X-ray-emitting hot background gas. Such shadows were indeed found in data from the X-ray satellite *ROSAT* launched in 1990. The group in Bonn found the shadow of the Draco Cloud (Burrows & Mendenhall 1991; Snowden et al. 1991) and of a cloud in Hercules (Lilienthal et al. 1992). However, both were shadows of lower-velocity clouds closer to the disk.

Two competing models for the distribution of the X-ray-emitting gas were debated: 1) a Local Hot Bubble plus an extragalactic background was favored by the Wisconsin group (see review by McCammon & Sanders 1990); 2) a multi-phase model of hot and cool pockets on all lines of sight, with the halo being predominantly hot and radiating, was favored by others (see Hirth et al. 1991). The competition for data and data rights of the *ROSAT* All Sky Survey, with which both models could be tested, was fierce.

4.4. DEVELOPMENTS IN THE ULTRAVIOLET

With the *IUE*, launched in 1978, numerous spectra of distant stars were obtained, showing absorption by C II, Mg II, and Fe II, etc. on halo sight lines (e.g. Savage & de Boer 1979, 1981; Pettini & West 1982). Savage & Massa (1987) detected substantial amounts of N V on halo sight lines in the direction of the Milky Way center. First attempts to measure extragalactic sources showed absorption at halo velocities (3C 273; York et al. 1983). The explosion of SN 1987A in the LMC provided the light to make in-depth studies of the gas in front of the LMC (de Boer et al. 1987). In particular the abundance of the metals (Blades et al. 1988) and the optical-depth profiles, spatial distribution, and nature of the Al III, Si IV, and C IV-containing gas (Savage et al. 1989) were investigated.

4.5. DISTANCES AND ABUNDANCES

In 1981 Ca II absorption was finally detected in an HVC – in the Magellanic Stream, in the direction of the AGN Fairall 9 (Songaila & York 1981; Songaila 1981). Songaila et al. (1985, 1986) claimed detections of complex A and C, which were later shown to be in error (Lilienthal et al. 1990).

By 1990 the Ca II K line had been detected in a few directions: toward PKS 0837−12 in complex WB (Robertson et al. 1991), and toward

NGC 3783 in HVC 287+22+240 (or WW 187) (West et al. 1985). However, HVC distances and metallicities still remained basically unknown. By this time it was clear that progress required observations of stars and AGNs fainter than about V=15 at 15 km s^{-1} resolution or better, which was just beyond the reach of most telescopes.

Without knowing distances, it is difficult to properly understand the distribution of HVC radial velocities. However, by using the statistics some progress can be made. An observational indication that halo gas rotates slower than the Milky Way disk came from the velocity of absorption lines found toward halo globular clusters (de Boer & Savage 1983, 1984). Combining this with the Center vs Anti-Center velocity asymmetry in Giovanelli's (1980) data, Kaelble et al. (1985) found that inflow (both vertical and radial) as well as rotation slightly slower than that in the disk are characteristics of the kinematics of most HVCs.

Progress was also made in understanding the Galactic Corona. Sembach & Savage (1992) analyzed the distribution of C IV and N V absorption, based on *IUE* data. Danly (1989) and Danly et al. (1992) studied the intermediate-velocity clouds with *IUE*, finding that the velocity range of the absorption appeared to increase with increasing distance from the plane, but only in the northern sky. However, these studies required bright, relatively nearby stars, often not projected onto H I HVCs, so they did not provide direct data on HVC distances.

4.6. HYPOTHESES FOR THE ORIGIN OF HVCS

Little progress was made in the theoretical understanding of HVCs in this decade, although the Galactic Fountain model started gaining favor. New models were proposed (e.g. HVCs as a polar ring – Haud 1988), but none of these has stood the test of time (see Ch. 13 for the current status of the polar ring idea).

5. Developments 1992–1999

During the nineties, HVC research came of age. At the beginning of the decade the old situation still prevailed, in which a small number of afficionados made slow progress on various aspects of the phenomenon. By 1999 the HVCs had become a hot topic that commanded widespread interest. The number of refereed HVC papers went up to an average of 10 a year, and by the end of the decade, the first separate HVC conference had taken place, in Canberra, Australia (Gibson & Putman 1999). The first distances and metallicities had been measured, making it possible to link individual clouds with some of the models proposed in the previous three decades, and indicating that examples might be found for several of these origins. HVC analogues were starting to be discovered in other galaxies, while Galactic HVCs were detected in Hα emission. Finally, Blitz et al. (1996) proposed that most (if not all) HVCs contained 10 times more dark matter than H I, and that they were the remnants of the formation of the Local Group, thus enlarging the context in which HVCs were to be understood.

5.1. SURVEYS

In the nineties, there were few 21-cm studies specifically aimed at observing HVCs. Nevertheless, four major developments took place. First, Kuntz & Danly (1996) used the Bell Labs Survey (Stark et al. 1992; declinations $>-40°$, 3° angular and 5 $\mathrm{km\,s^{-1}}$ velocity resolution) to create the first IVC catalog, after 20 years finally making progress on IVCs.

Second, in this timespan a new survey was done using a yet-again upgraded *Dwingeloo* telescope. By 1997 this produced what is now known as the Leiden-Dwingeloo Survey (*LDS*; Hartmann & Burton 1997), covering the whole sky visible from Dwingeloo (declination $>-30°$) on a $0.^\circ5\times0.^\circ5$ grid, with 1 $\mathrm{km\,s^{-1}}$ velocity resolution and 0.07 K rms. An important improvement over previous surveys is that all the *LDS* data have been corrected for stray radiation. This survey contains most (~90%) of the detections in the earlier Hulsbosch & Wakker (1988) data, but for the first time also comparable data for the IVCs. A proper analysis of the HVC and IVC information in this dataset is still lacking.

Third, a southern complement to the *LDS* was done in Argentina, using the *Villa Elisa* telescope (Arnal et al. 2000); the HVCs in this survey were listed by Morras et al. (2000). A global analysis of the new surveys is given in Ch. 2. The current status of research on IVCs is presented in Ch. 4.

Fourth, the *HIPASS* (H I Parkes All Sky Survey) was completed (Barnes et al. 2001). This survey aimed at detecting galaxies out to several tens of Mpc, but it also allowed the mapping of Galactic HVCs at declinations $<0°$ at $17'$ angular resolution (and full angular coverage), though only at 26 $\mathrm{km\,s^{-1}}$ velocity resolution. Putman et al. (2002) used these data to produce the most detailed map yet of the Magellanic Stream, including the first clear H I map of the Leading Arm (Putman et al. 1998). Chapter 5 presents these data, and discusses the new results concerning the Stream.

Finally, from studies of the small-scale structure of the HVCs (see Ch. 7) some authors concluded that it is possible to use the morphology observed at high angular resolution to uncover evidence for interactions of the HVCs with their environment. This work is summarized in Ch. 12.

5.2. EXTRAGALACTIC HVCS AT 21 CM

By the end of the eighties, H I interferometers had finally become sensitive enough that searches for HVCs in external galaxies were possible. This search was pushed hard by Sancisi in Groningen. A first check of old data showed the possibilities (Wakker et al. 1989). The first bona-fide extragalactic HVCs were discovered in M 101 by van der Hulst & Sancisi (1988). These objects have velocities of 80 to 150 km s^{-1} relative to the underlying disk, and appear more massive than HVCs in the Milky Way. Several other galaxies were observed in great detail in the ensuing years, and H I with deviating velocities was found to be common. In a series of papers, Schulman et al. (1994, 1996, 1997) observed several galaxies with *Arecibo* and the Very Large Array (*VLA*), concluding that the high-velocity gas seems to be related to the underlying star-formation activity. High-sensitivity interferometer observations also showed many clouds unrelated to disk gas. Chapter 6 presents a review of this work, as well as a discussion of the post-1999 results and the implications for understanding the Galactic HVCs.

5.3. Hα OBSERVATIONS

Songaila et al. (1985) claimed to have detected Hα emission from complex C. However, the detection was marginal, and the paper had little impact (when Tufte et al. (1998) reobserved this direction, they found that the Hα emission is much brighter). Reynolds (1987) reported several non-detections, but Kutyrev & Reynolds (1989) detected faint emission associated with HVC 168−43−280. The next detection of high-velocity Hα was made by Weiner & Williams (1996), for a direction toward the Magellanic Stream. Then, Tufte et al. (1998) found emission from complexes A, C and M, and Bland-Hawthorn et al. (1998) detected complex GCP. These data appeared to hold the promise of determining HVC distances, by assuming that the Hα emission was the result of recombination after photoionization, an idea first proposed for HVCs by Ferrara & Field (1994). However, it has turned out to be more complicated than that, and more observations and theory will be necessary to properly interpret the Hα emission. A review of the current status of this work is given in Ch. 8, while the implications of the Hα detections are discussed in Ch. 16.

5.4. DISTANCES AND ABUNDANCES

The years 1991 to 1998 saw an explosion of absorption-line studies of HVCs, mostly based on data from space observatories: *IUE*, and the Hubble Space Telescope (*HST*). Danly et al. (1993) derived the first upper distance limit (4.5 kpc to cloud M III). Then de Boer et al. (1994) set a lower limit of 2 kpc to the distance of complex C, Wakker et al. (1996) found a lower limit of 4 kpc for complex A, and Wakker et al. (1998) used the *IUE* archive to derive a lower limit of 5 kpc for complex H. Work on IVC distances proceeded mostly with *IUE* (Kuntz & Danly 1996). Lu et al. (1994, 1998) combined data from *HST* and the Australia Telescope Compact Array (*ATCA*) to derive an abundance of 0.25 times solar for a bright high-positive-velocity HVC toward NGC 3783. Together with a new model for the Magellanic Stream (Gardiner & Noguchi 1996), this result allowed to exclude the proposal by Moore & Davis (1994) that the Magellanic Stream is caused by ram-pressure stripping rather than tidal forces.

Ground-based work did not languish either. Many results for IVCs were obtained by the group in Belfast, led by Keenan, using observations of blue halo and globular cluster stars with distances up to a few kpc. Van Woerden, Schwarz, Wakker & Peletier had many runs in the late 1980s and the 1990s with the Isaac Newton and William Herschel telescopes at La Palma, taking spectra of Blue Horizontal Branch (BHB) and RR Lyrae stars. Although a large fraction of the allocated nights were lost to bad weather (since complexes A and C are high in the sky in early spring), in 1997 complex A was detected in absorption toward the RR Lyrae star AD UMa, establishing the first HVC distance bracket (van Woerden et al. 1999). During the same series of observations, the first detections of Ca II in complex C were made against the Seyferts Mrk 290 and PG 1351+640 (Wakker et al. 1996). This result was used to obtain *HST* time, which showed that complex C has a metallicity ~0.1 times solar, firmly establishing that it does not have a Galactic origin (Wakker et al. 1999). Chapter 10 describes these and post-1999 results on distance and abundance determinations in detail.

5.5. PROGRESS IN THE ULTRAVIOLET

The sensitivity of *IUE* was insufficient to observe extragalactic targets at high resolution, except for the bright supernova SN 1993J in M 81. In its spectrum de Boer et al. (1993) found an HVC containing both low-ionization-stage metals (C II, Mg II, etc.) and C IV, at velocities clearly indicating infall onto M 81.

Savage et al. (1997) analyzed high-resolution *HST* observations of C IV and N V toward extragalactic objects, and estimated the scaleheight of the hot gas, deriving ~4 kpc for C IV, and ~2 kpc for N V. This difference shows a complication with the observational interpretation of the highly-ionized atoms in terms of Spitzer's hot halo – some of these ions may be photoionized. The presence of hot gas in the lower halo now is firmly established, however, vindicating Spitzer's idea that neutral halo clouds are confined by a source of external pressure.

The long absence of observing facilities in the far-UV (912 to 1200 Å) after the termination of *Copernicus* was ended in the middle of the decade, when the Space Shuttle experiment named "Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometers" (*ORFEUS*) flew twice, containing the Berkeley medium-, the Tübingen-Heidelberg high-, and the Princeton very-high-resolution spectrographs. Spectra of a fair number of halo stars suggested a scale height for O VI gas on the order of 5 kpc (Widmann et al. 1998); Savage et al. (2003) later derived 2.3 kpc. H_2 was also discovered in the HVC projected against the LMC (Richter et al. 1999).

6. New developments since 1999

6.1. THE LOCAL GROUP HYPOTHESIS

Broad interest in HVCs was generated by the proposal by Blitz et al. (1996, 1999) that HVCs represent the missing population of dark-matter halos in the Local Group (see Ch. 14 for a full description). Although few people familiar with the details of the HVC phenomenon accepted this idea, it generated a lot of work in trying to understand HVC metallicities, mapping HVC Hα emission and comparing the gas content of the Local Group with that of other galaxy groups (see Chaps. 2, 6, 8, 15). The original proposal by Blitz et al. (1999) seems untenable, but a variant was proposed by Braun & Burton (1999), who singled out the small HVCs as possible Local Group objects, calling these objects "Compact HVCs" (CHVCs). An extensive study of these CHVCs formed the basis of another HVC thesis, published as a series of papers (de Heij et al. 2002a, b, c) (see also Ch. 15). Note, however, that the larger HVCs may just be nearby examples of the same population, as Blitz et al. (1999) proposed.

6.2. RE-OPENING THE FAR-ULTRAVIOLET

The launch of the Far Ultraviolet Spectroscopic Explorer (*FUSE*) occurred in June of 1999. With it, Spitzer's hot Corona is finally being studied in detail. *FUSE* (shown in Fig. 5) also has revolutionized the study of HVCs, providing many measurements of metallicities, and showing the ubiquity of the highly-ionized HVCs, which were previously only known from a few directions (Sembach et al. 1999). Highlights of the discoveries made with *FUSE* are summarized in Chaps. 9, 10 and 11. The papers based on *FUSE* and *HST* data by Murphy et al. (2000), Gibson et al. (2001), Richter et al. (2001), Collins et al. (2003) and Tripp et al. (2003) list measurements of many ions for complex C. *FUSE* also found H_2 in some HVCs and many IVCs (Richter et al. 2003; Ch. 9).

The O VI absorption associated with the highly-ionized HVCs was an-

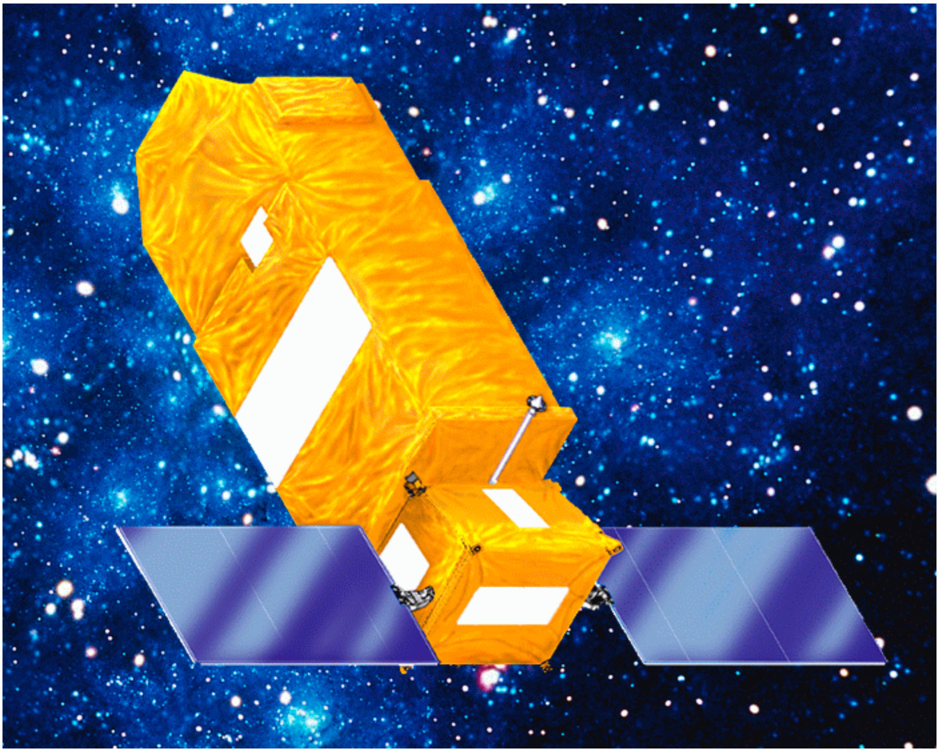

Figure 5. Artist impression of *FUSE* in orbit. Available on the *FUSE* web site http://fuse.pha.jhu.edu/Photos/pub quality/bestof fuse.html. Graphic by Orbital Sciences Corp.

alyzed by Wakker et al. (2003), Sembach et al. (2003) and Savage et al. (2003) in a special issue of the ApJ Supplement (see summary in Ch. 11). The properties of the O VI indicate the presence of hot gas surrounding complex C (Fox et al. 2004) and the Magellanic Stream, suggesting a new kind of Galactic Corona, one much larger (out to at least 50 kpc) than envisioned by Spitzer. In many directions high-velocity O VI absorption without associated high-velocity H I is found, which might represent hot gas in the Local Group. More study of this new kind of HVC is underway.

Many questions about the origin and properties of the HVCs remain open. Chapters 13 and 16 discuss the evidence for some of the proposed origins. Chapter 17 presents directions for future work.

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